

DUBLIN CITY UNIVERSITY

ELECTRONIC AND COMPUTER ENGINEERING

---

## Streaming Audio Server with Listener-Tracking Embedded Clients

---



Authors

Michael Lenehan [michael.lenehan4@mail.dcu.ie](mailto:michael.lenehan4@mail.dcu.ie)

Supervisor

Martin Collier [martin.collier@mail.dcu.ie](mailto:martin.collier@mail.dcu.ie)

# Contents

<b>1 Acknowledgments</b>	<b>6</b>
<b>2 Declaration</b>	<b>6</b>
<b>3 Abstract</b>	<b>7</b>
<b>4 Introduction</b>	<b>8</b>
<b>5 Background Literature Survey</b>	<b>9</b>
5.1 Hardware Requirements . . . . .	9
5.2 Open Source Software . . . . .	11
5.3 Listener Tracking . . . . .	13
<b>6 Concepts, Modelling, and Design</b>	<b>14</b>
6.1 Audio Streaming . . . . .	14
6.2 Listener Tracking . . . . .	15
6.3 Extensibility . . . . .	17
<b>7 Experimental Equipment and Procedures</b>	<b>18</b>
7.1 Experimental Equipment Requirements . . . . .	18
7.2 Experimental Procedures . . . . .	18
<b>8 Implementation and Testing</b>	<b>22</b>
8.1 Audio Server Software Implementation . . . . .	22
8.2 Audio Server Software Testing . . . . .	23
8.3 Listener Tracking Implementation . . . . .	24
8.4 Listener Tracking Testing . . . . .	24
<b>9 Results and Analysis</b>	<b>25</b>
9.1 Audio Server Software . . . . .	25
9.2 Listener Tracking . . . . .	35
<b>10 Ethics</b>	<b>37</b>
10.1 Audio Tracks . . . . .	37
10.2 Listener Tracking . . . . .	40
<b>11 Conclusions and Recommendations</b>	<b>41</b>
11.1 Conclusions . . . . .	41
11.2 Recommendations . . . . .	41
<b>12 Appendix</b>	<b>42</b>
12.1 Audio Server Software Munin Data . . . . .	42
12.2 Audio Server Software Munin Data Tables . . . . .	63

# List of Tables

7.1 Required Experimental Equipment . . . . .	18
9.1 MPD Server and SnapClient Device Network Parameters . . . . .	26
9.2 MPD Server and SnapClient Device System Parameters . . . . .	27
9.3 MPD Server and SnapClient Device Sensor Parameters . . . . .	28
9.4 Mopidy Server and SnapClient Device Network Parameters . . . . .	29
9.5 Mopidy Server and SnapClient Device System Parameters . . . . .	30
9.6 Mopidy SnapClient Device Sensor Parameters . . . . .	31
9.7 Volumio Server and SnapClient Device Network Parameters . . . . .	32
9.8 Volumio Server and SnapClient Device System Parameters . . . . .	33
9.9 Volumio Server and SnapClient Device Sensor Parameters . . . . .	34
9.10 Server Device Beacon Bluetooth Distance Measurements . . . . .	35
9.11 "Client1" Device Beacon Bluetooth Distance Measurements . . . . .	36
9.12 "Client2" Device Beacon Bluetooth Distance Measurements . . . . .	36
12.1 MPD SnapClient Device Disk Parameters . . . . .	63
12.2 MPD Server Device Disk Parameters . . . . .	63
12.3 MPD SnapClient Device Network Parameters . . . . .	64
12.4 MPD Server Device Network Parameters . . . . .	65
12.5 MPD SnapClient Device Process Parameters . . . . .	65
12.6 MPD Server Device Process Parameters . . . . .	66
12.7 MPD SnapClient Device System Parameters . . . . .	66
12.8 MPD Server Device System Parameters . . . . .	67
12.9 MPD SnapClient Device Sensor Parameters . . . . .	67
12.10MPD Server Device Sensor Parameters . . . . .	68
12.11Mopidy SnapClient Device Disk Parameters . . . . .	68
12.12Mopidy Server Device Disk Parameters . . . . .	69
12.13Mopidy SnapClient Device Network Parameters . . . . .	70
12.14Mopidy Server Device Network Parameters . . . . .	71
12.15Mopidy SnapClient Device Process Parameters . . . . .	71
12.16Mopidy Server Device Process Parameters . . . . .	72
12.17Mopidy SnapClient Device System Parameters . . . . .	72
12.18Mopidy Server Device System Parameters . . . . .	73
12.19Mopidy SnapClient Device Sensor Parameters . . . . .	73
12.20Mopidy Server Device Sensor Parameters . . . . .	74
12.21Volumio SnapClient Device Disk Parameters . . . . .	74
12.22Volumio Server Device Disk Parameters . . . . .	75
12.23Volumio SnapClient Device Network Parameters . . . . .	76
12.24Volumio Server Device Network Parameters . . . . .	77
12.25Volumio SnapClient Device Process Parameters . . . . .	77
12.26Volumio Server Device Process Parameters . . . . .	78
12.27Volumio SnapClient Device System Parameters . . . . .	78
12.28Volumio Server Device System Parameters . . . . .	79
12.29Volumio SnapClient Device Sensor Parameters . . . . .	79
12.30Volumio Server Device Sensor Parameters . . . . .	80

# List of Figures

5.1 BeagleBone Black [1] . . . . .	9
5.2 Asus TinkerBoard . . . . .	10
5.3 Raspberry Pi 3 Model B+ [2] . . . . .	10
5.4 Adafruit I2S Audio Bonnet [3] . . . . .	11
6.1 Floor Plan with Downstairs (Left), Upstairs (Right), and Raspberry Pi Locations (Represented by 'O's) . . . . .	14
10.1 Spotify Paying Subscribers in Millions from Q1 2015 to Q4 2018 . . . . .	38
10.2 Recorded Music Revenues for the United States [4] . . . . .	39
12.1 MPD Disk I/O on Client and Server Device . . . . .	42
12.2 MPD Client and Server Device Disk Latency . . . . .	42
12.3 MPD Client and Server Device Disk Throughput . . . . .	43
12.4 MPD Client and Server Device Disk Utilization . . . . .	43
12.5 MPD Client and Server Device Firewall Throughput . . . . .	43
12.6 MPD Client and Server Device Eth Errors . . . . .	44
12.7 MPD Client and Server Device Eth Traffic . . . . .	44
12.8 MPD Client and Server Device Wlan Errors . . . . .	44
12.9 MPD Client and Server Device Wlan Traffic . . . . .	44
12.10MPD Client and Server Device Netstat . . . . .	45
12.11MPD Client and Server Device Processes . . . . .	45
12.12MPD Client and Server Device Number of Threads . . . . .	45
12.13MPD Client and Server Device Load Average . . . . .	46
12.14MPD Client and Server Device Individual Interrupts . . . . .	46
12.15MPD Client and Server Device Interrupts and Context Switches . . . . .	46
12.16MPD Client and Server Device Memory Usage . . . . .	47
12.17MPD Client and Server Device Fork Rate . . . . .	47
12.18MPD Client and Server Device CPU Usage . . . . .	47
12.19MPD Client and Server Device CPU Frequency . . . . .	48
12.20MPD Client and Server Device CPU Frequency Scaling . . . . .	48
12.21MPD Client and Server Device CPU Temperature . . . . .	48
12.22Mmopidy Disk I/O on Client and Server Device . . . . .	49
12.23Mopidy Client and Server Device Disk Latency . . . . .	49
12.24Mopidy Client and Server Device Disk Throughput . . . . .	49
12.25Mopidy Client and Server Device Disk Utilization . . . . .	49
12.26Mopidy Client and Server Device Firewall Throughput . . . . .	50
12.27Mopidy Client and Server Device Eth Errors . . . . .	50
12.28Mopidy Client and Server Device Eth Traffic . . . . .	50
12.29Mopidy Client and Server Device Wlan Errors . . . . .	51
12.30Mopidy Client and Server Device Wlan Traffic . . . . .	51
12.31Mopidy Client and Server Device Netstat . . . . .	51
12.32Mopidy Client and Server Device Processes . . . . .	52
12.33Mopidy Client and Server Device Process Priority . . . . .	52
12.34Mopidy Client and Server Device Number of Threads . . . . .	52
12.35Mopidy Client and Server Device Load Average . . . . .	53

12.36Mopidy Client and Server Device Individual Interrupts . . . . .	53
12.37Mopidy Client and Server Device Interrupts and Context Switches . . . . .	53
12.38Mopidy Client and Server Device Memory Usage . . . . .	54
12.39Mopidy Client and Server Device Fork Rate . . . . .	54
12.40Mopidy Client and Server Device CPU Usage . . . . .	54
12.41Mopidy Client and Server Device CPU Frequency . . . . .	55
12.42Mopidy Client and Server Device CPU Frequency Scaling . . . . .	55
12.43Mopidy Client and Server Device CPU Temperature . . . . .	55
12.44Volumio Disk I/O on Client and Server Device . . . . .	56
12.45Volumio Client and Server Device Disk Latency . . . . .	56
12.46Volumio Client and Server Device Disk Throughput . . . . .	56
12.47Volumio Client and Server Device Disk Utilization . . . . .	56
12.48Volumio Client and Server Device Firewall Throughput . . . . .	57
12.49Volumio Client and Server Device Eth Errors . . . . .	57
12.50Volumio Client and Server Device Eth Traffic . . . . .	57
12.51Volumio Client and Server Device Wlan Errors . . . . .	58
12.52Volumio Client and Server Device Wlan Traffic . . . . .	58
12.53Volumio Client and Server Device Netstat . . . . .	58
12.54Volumio Client and Server Device Processes . . . . .	59
12.55Volumio Client and Server Device Processes . . . . .	59
12.56Volumio Client and Server Device Number of Threads . . . . .	59
12.57Volumio Client and Server Device Load Average . . . . .	60
12.58Volumio Client and Server Device Individual Interrupts . . . . .	60
12.59Volumio Client and Server Device Interrupts and Context Switches . . . . .	60
12.60Volumio Client and Server Device Memory Usage . . . . .	61
12.61Volumio Client and Server Device Fork Rate . . . . .	61
12.62Volumio Client and Server Device CPU Usage . . . . .	61
12.63Volumio Client and Server Device CPU Frequency . . . . .	62
12.64Volumio Client and Server Device CPU Frequency Scaling . . . . .	62
12.65Volumio Client and Server Device CPU Temperature . . . . .	62

# **1 Acknowledgments**

I would like to thank my project supervisor, Dr. Martin Collier. He provided guidance and assistance with all aspects of this project, and his knowledge and insight on the topic were invaluable. I would also like to thank Dr. Gabriel-Miro Muntean, who acted as the second assessor for this project. His insight into testing practices, which gave greater clarity to the overall project results.

# **2 Declaration**

I declare that this material, which I now submit for assessment, is entirely my own work and has not been taken from the work of others, save and to the extent that such work has been cited and acknowledged within the text of my work. I understand that plagiarism, collusion, and copying are grave and serious offences in the university and accept the penalties that would be imposed should I engage in plagiarism, collusion or copying. I have read and understood the Assignment Regulations set out in the module documentation. I have identified and included the source of all facts, ideas, opinions, and viewpoints of others in the assignment references. Direct quotations from books, journal articles, internet sources, module text, or any other source whatsoever are acknowledged and the source cited are identified in the assignment references. This assignment, or any part of it, has not been previously submitted by me or any other person for assessment on this or any other course of study.

I have read and understood the DCU Academic Integrity and Plagiarism at [https://www4.dcu.ie/sites/default/files/policy/1%20-%20integrity\\_and\\_plagiarism\\_ovpaa\\_v3.pdf](https://www4.dcu.ie/sites/default/files/policy/1%20-%20integrity_and_plagiarism_ovpaa_v3.pdf) and IEEE referencing guidelines found at <https://loop.dcu.ie/mod/url/view.php?id=448779>.

Name: Michael Lenehan Date: 08/04/2019

### **3 Abstract**

Open-Source audio server softwares are numerous. The most popular available options for embedded linux devices are intended for use as “headless” audio devices, controlled over the network, and outputting their audio locally. With a large number of subscription based audio streaming services available, such as Spotify, Tidal, and Google Play Music, there is an increasing need for an option to stream a users own music, from a central storage device, to their client device of choice.

The addition of listener tracking allows a user to play audio through multiple speakers as they traverse a space, such as their home, without needing to play music through all available speakers, or without turning device volumes up or down.

## 4 Introduction

There are many options for open-source audio streaming available to users. A number of configurations of the available open-source audio streaming hardware and software allow for end-users to play locally stored audio on a so-called “Headless” system, whereby the server software is controlled remotely by the user.

In recent years, a movement away from locally stored audio solutions has taken place. Subscription based audio streaming services such as Spotify exist to allow users access audio which they have no access to physical copies of. While this trend exists, an optimal server software solution would serve both locally stored, and streaming audio options to listeners.

This project explores the idea of implementing a streaming server which allows users access a stored collection of audio, from any connected device, and to stream this audio to the nearest available client device. A solution must offer an accessible user experience, and importantly provide good quality playback, achieved through the combination of chosen software and hardware.

# 5 Background Literature Survey

## 5.1 Hardware Requirements

### Embedded Linux Devices

There are a number of Linux based embedded systems which may be configured to act as an audio streaming server with the appropriate software. Commonly used systems include the Raspberry Pi 3 Model B+, BeagleBone Black, and ASUS Tinker Board. There are differences between these development platforms which allow them more or less suitability for the purposes of this project.

The BeagleBone Black (BBB) is a low cost platform, with compatibility for many Linux distributions. The device has on board flash memory, Ethernet and HDMI outputs. There is also on board  $I^2S$  support, allowing for hardware Digital to Analog Converters (DACs) to be connected. The BBB has 512MB of DDR3 RAM, and a 1GHz ARM processor on board [1].

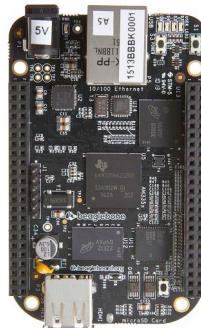


Figure 5.1: BeagleBone Black [1]

The ASUS Tinker Board is a small form-factor Single Board Computer (SBC). The computer has Gigabit Ethernet, HDMI output, multiple IO, including 40 GPIO pins and 4 USB ports. The 1.8GHz ARM based CPU provides high performance when coupled with the 600MHz GPU and 2GB of dual-channel DDR3 RAM. This SBC also supports the  $I^2S$  audio protocol [5].

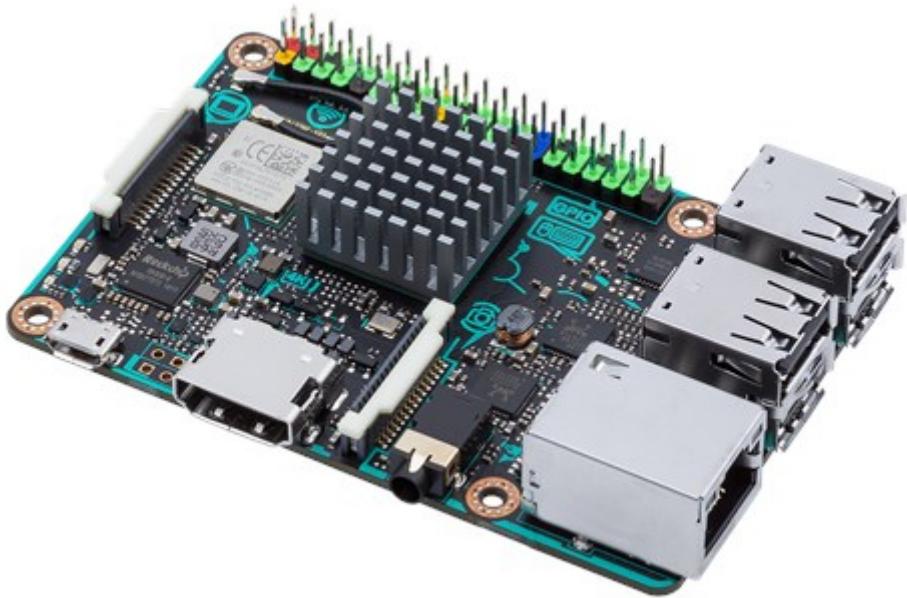


Figure 5.2: Asus TinkerBoard  
[5]

The Raspberry Pi 3 Model B+ is one of the most commonly used embedded Linux development platforms. The device has a 1.4GHz ARM processor, 1GB of DDR2 RAM, Gigabit Ethernet, Bluetooth Low Energy, and multiple IO ports. Again, this board supports the  $I^2S$  protocol, with outputs on its GPIO [2].



Figure 5.3: Raspberry Pi 3 Model B+ [2]

Each of the aforementioned options offers different levels of performance at different price points. The BeagleBone Black is both the cheapest and least powerful option. The ASUS

TinkerBoard is the most powerful and most expensive option, while the Raspberry Pi offers comparatively high performance at a mid price. The benefits and costs of these Single Board Computers must be compared in order to choose that which is most appropriate for the application of serving and streaming audio.

For the purposes of this project, the Raspberry Pi Model 3 B+ was chosen. This platform has a large user base, and an active online community, allowing for a more user friendly experience, especially with regards to aspects such as initial setup and software installation. The Raspberry Pi also has a large number of available add-on boards, commonly referred to as “Hats” or “Bonnets”. These boards may be used to give additional functionality to the Raspberry Pi, with boards available for purposes such as adding display capabilities, numerous sensors, and, as is applicable to this project, audio DAC and amplifiers.

## Audio DAC

As previously mentioned, there are a number of amplifier and DAC add-on options for the Raspberry Pi 3 Model B+. Some of the most popular options available are from HiFiBerry, including their HiFiBerry Dac+ Pro. This board offers RCA output, with dual-domain low-jitter clocks [6].

The option chosen was the Adafruit I2S Audio Bonnet for Raspberry Pi. This DAC also utilises the  $I^2S$  audio protocol, through the UDA1334A stereo DAC. The board outputs audio via a standard 3.5mm audio jack, with the option of soldering RCA jacks to the PCB.

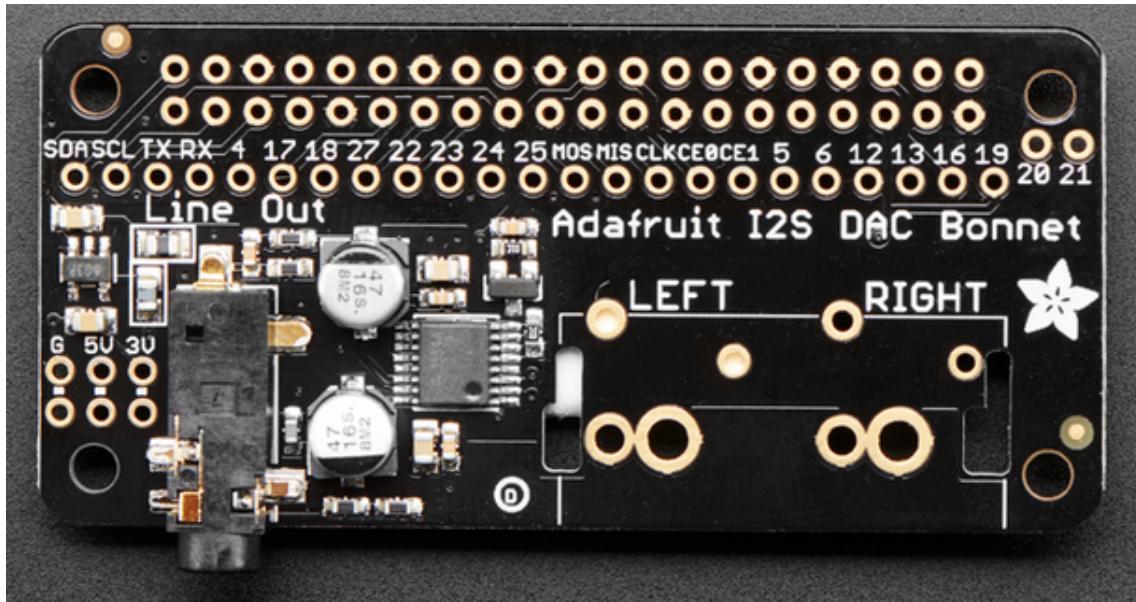


Figure 5.4: Adafruit I2S Audio Bonnet [3]

## 5.2 Open Source Software

A number of software solutions exist for streaming audio from low powered hardware. Options such as MPD - the Music Player Daemon -, Mopidy, and Volumio, allow for users to play music on the system. These options are typically used to implement headless audio

player setups, with the user sending messages over the network to control the player.

While these options provide much of the basic required functionality, they are not a suitable solution for the project. The required functionality from the software will be to stream media from the server system to the client system. This functionality exists in these open-source software options, but requires modifications to be made to configuration files in order to be implemented.

Audio software PulseAudio may also be utilised, as it is often found on Linux based systems. PulseAudio is a sound server which routes audio from the running application to the selected output device. On Linux systems, this is used to send audio output to the system speakers, or connected USB devices. However, the functionality exists to pass the output audio over the network to a specified address [7].

## **MPD**

MPD is a server-side audio application, available on Debian based Linux platforms, such as Raspbian, via the standard “apt” package manager repositories. Via the available configuration files, parameters such as the music directory, audio output device, audio encoder and decoder plugins, and audio format settings may be set. MPD allows for playback of a number of audio formats, including WAV, FLAC, and MP3, and supports both FIFO, and HTTPD streaming [8].

## **Mopidy**

Mopidy is a server-side audio application, written in python, which extends the functionality of MPD. It is available on Debian based Linux platforms, such as Raspbian, via the standard “apt” package manager repositories. In its default configuration, Mopidy acts as a local media server, based on MPD. The advantage of Mopidy however, lies in its extensibility via available “Extensions”. These extensions include Spotify connectivity, allowing users not only access to locally stored audio files, but also to streaming audio.

## **Volumio**

Volumio is a stand alone Linux based operating system, or “distribution”, which has been designed specifically for audio playback [9]. It is designed to be used on low powered computers, such as the Raspberry Pi. Playback is accessible via a web application user interface. The playback functionality of Volumio is controlled by an MPD server.

## **Snapcast**

Snapcast is a time synchronized client-server audio player. Snapcast reads audio data from the server device, and, utilising the TCP protocol, sends the data to all connected network client devices. Using the aforementioned audio playback softwares, audio data can be passed to a file, which Snapcast may then read from. Synchronicity is achieved by passing the server’s time to all clients, allowing their received data buffers to be played back at the appropriate timing.

## **5.3 Listener Tracking**

Another aspect of the project is the listener tracking and audio routing. There are multiple protocols which may be used in order to determine location of a mobile device. Bluetooth “Beacons” or Access Points are used, sending a packet to the device, the signal strength may be used to calculation and approximate distance [10]. Using filtering techniques, distances may be calculated, using Bluetooth, to an accuracy of approximately 1.8 meters [10].

Location using WiFi may provide greater accuracy, however requires specialised hardware [11]. The 802.11AC WiFi standard allows for the use of Beamforming, in which multiple antennas transmit at once, allowing for the targeted transmission of data [12]. Using Angle-of-Arrival (AoA), and Time-of-Flight (ToF), and Multiple Signal Classification (MUSIC) algorithms, the distance and direction from the Access Point may be determined [13]. The operations which must be performed are complex, and dependent on the hardware being used. As such, less complex solutions, such as RSSI, may be implemented, however there is also a reduction in accuracy.

### **Bluetooth Beacons**

A number of Bluetooth Beacon Specifications are currently accessible for use on embedded Linux platforms. These specifications include AltBeacon [14], from Radius Networks, and Eddystone [15] from Google Beacon Platform. These specifications allow for ranging requests, which provide the requesting device with a distance estimate, based on the received signal strength indication (RSSI) from beacon device to the user device.

### **802.11MC WiFi**

The 802.11MC WiFi protocol provides location determination functionality, using Round Trip Time (RTT). This protocol, if implemented on the embedded Linux platforms, would allow for ranging requests to be performed from Android devices on API level 28 (Android 9 “Pie”) [16].

# 6 Concepts, Modelling, and Design

There are two main design aspects to this project, firstly the audio streaming server, with multiple connected devices, and secondly, the listener tracking. Outlined are the proposed solutions to each of these aspects, along with any complications or limitations faced.

## 6.1 Audio Streaming

The proposed design solution for the implementation of the audio streaming system utilizes three Raspberry Pi 3 Model B+, each with a DAC for outputting high quality audio. The chosen audio server software runs on one device, alongside the streaming server, with the streaming clients running on the other devices.

Figure 6.1 shows the placement of the client and server devices, with the server being the lower of the devices on the downstairs portion of the floor plan. This device is connected to the network router/access point. Each of the client devices is connected to the network via Wi-Fi.

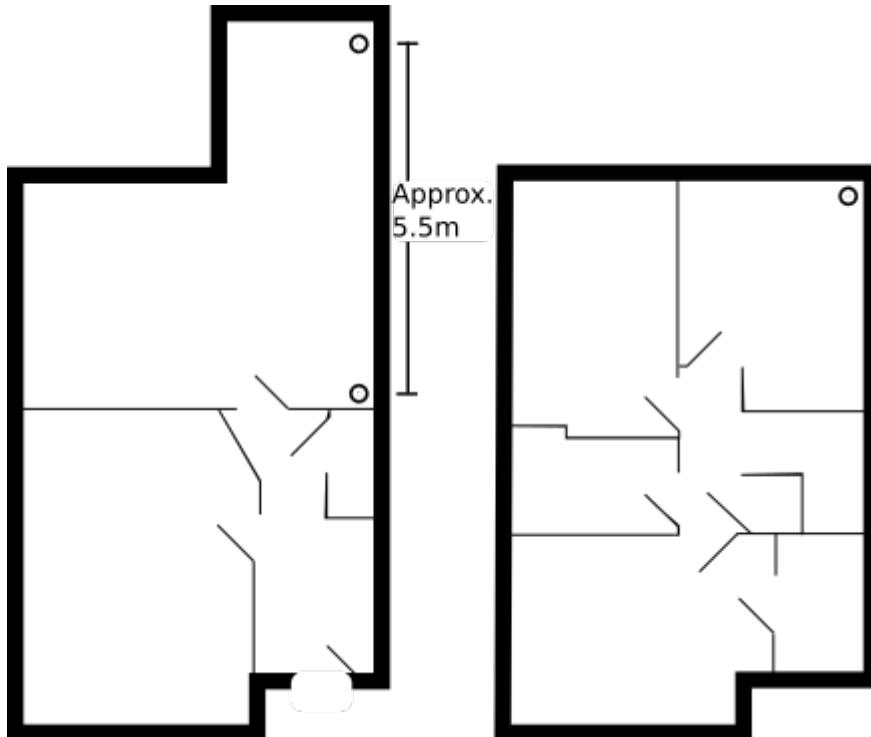


Figure 6.1: Floor Plan with Downstairs (Left), Upstairs (Right), and Raspberry Pi Locations (Represented by 'O's)

Utilising Snapcast, multiple client devices may be connected to a central server device, with audio playback controlled from this server device, and transmit across the network for synchronous playback on the client devices.

## 6.2 Listener Tracking

Listener tracking is implemented using a combination of Bluetooth Low Energy Beacons, and an accompanying Android application. The BLE Beacons must be available to be scanned from the Android application, which, in turn, must control the volume of the audio client devices,

### Beacons

The AltBeacon BLE Beacon protocol is used for proximity data. The audio client devices are configured using modified “BlueZ” example code [17]. AltBeacon is an open-source implementation of Apple’s iBeacon standard. The AltBeacon device constantly transmits data, which is intended to be read by the Android application for the purpose of ranging.

While there is an “Android Beacon Library”, which allows for ranging of Google’s Eddystone Beacons [18], this library is not available in Flutter, which negates the cross-platform compatibility advantage held by Flutter applications. This is discussed further in the following section.

The AltBeacon protocol has a data structure which has a number of significant bytes. Bytes 7 and 8 must be set to “0xBEAC”, which represents the AltBeacon advertisement code [19]. Bytes 9-29 are reserved for the unique beacon identifier. In order to correctly calibrate the AltBeacon, the average RSSI value at a distance of 1 meter from the beacon device must be measured, and this value placed in byte 29.

### Android Application

The proposed Android application, built using Google’s “Flutter” framework, connects to the audio server, allowing for the control of volume parameters. This is achieved via the transmission of JSON encoded messages, as defined in the Snapcast JSON RPC API [20], via a TCP socket connection from the application to the server device, on port 1705. Given an audio client device ID, which may be parsed from a server response message, the client devices volume can be adjusted, or muted from within the application. In order to create a JSON message in Dart, the language used by Flutter, a number of classes and constructors are required. The following is the Snapcast command for adjusting the volume of a connected client device.

Listing 6.1: Example Snapcast ”Client.SetVolume” Request

```
{ "id":8,  
  "jsonrpc":"2.0",  
  "method":"Client.SetVolume",  
  "params":  
    { "id":"00:21:6a:7d:74:fc",  
      "volume":{ "muted":false, "percent":74}  
    }  
}
```

As both the “params” and “volume” fields have multiple arguments, they each require separate constructors, as follows:

Listing 6.2: Dart JSON ”volume” Field Constructor

```
JSONVolume( bool mute, int percent){
```

---

```

    this.volume[ "muted" ] = mute;
    this.volume[ "percent" ] = percent;
}

```

---

Listing 6.3: Dart JSON ”params” Field Constructor

---

```

JSONParams( String id , bool mute, int percent){
    this.params[ "id" ] = id;
    this.params[ "volume" ] = JSONVolume(mute,
    percent).volume;
}

```

---

Finally, the Dart equivalent of the JSON message can be constructed:

Listing 6.4: Dart JSON Client.SetVolume Constructor

---

```

ClientVolume( String id , bool mute, int percent){
    this.jsonMessage[ "id" ] = 8;
    this.jsonMessage[ "jsonrpc" ] = "2.0";
    this.jsonMessage[ "method" ] = "Client . SetVolume";
    this.jsonMessage[ "params" ] = JSONParams(id , mute,
    percent).params;
    this.messageString = json.encode(this.jsonMessage)
    + "\r\n"; // '\r\n' required for newline delimited
    // JSON messages
}

```

---

The encoded message can be transmit to the server using the “Socket.connect(IP, Port)”, and “Socket.write(String)” methods. An issue arose however in receiving the JSON response from the Snapcast server, with notification responses being received when audio playback was started or stopped, but no responses being received to the “Server.GetStatus”, or “Client.SetVolume” requests. This meant that client ID’s could not be parsed from the server response, and, as such, client ID’s were required to be hard-coded.

The BLE Beacon ranging is implemented by utilising the Flutter “beacons” plugin, which supports monitoring, and ranging of both iBeacon and AltBeacon Bluetooth Beacons [21]. This plugin’s GitHub repository gives an example application, which, when passed a Beacon ID performs a ranging request, printing the RSSI value to the screen. Also provided are methods for ranging while the application is in the background.

Listing 6.5: Flutter Beacons Generic Beacon Ranging

---

```

Beacons.ranging( region: BeaconRegion(
    identifier: 'test',
    ids: [ 'id1' , 'id2' , 'id3' ],
),
inBackground: true,
).listen(( result ) {
    final Beacon beacon = result.beacons.first;
});

```

---

When combined with the volume control code, the intended implementation is to increase volume as the listener moves closer to the client device, and decrease the volume on the device being moved away from. This implementation was not completed due to issues faced in Dart development, with packages inconsistently loading correctly. This could be due to the relative infancy of the Flutter framework, or due to an inexperience in developing using Flutter and Dart. The advantages of using Flutter however, are that applications, using standard packages, and not platform specific code, may be executed on both Android and iOS devices, for example, the JSON volume control code could be executed on an iOS device, if available.

### **6.3 Extensibility**

An ideal solution to the system proposed in this project would provide extensibility, both in the number of clients, and in teh number of concurrent users. With the implementation of Snapcast, any number of client devices may be used, so long as the network can handle the number of connections. Many router/access points combinations have a limit on the nnumber of Wi-Fi devices which can be connected to the network at once, with the Sky Q Hub used having a maximum number of 64 connected devices [22].

As devices are added, the accuracy of the BLE beacons could act as an obstruction to extending the number of devices. Differences in accuracy between closely placed beacons could result in the scanning application choosing to route audio to the incorrect client device. However, as Snapcast can group client devices, and modify group volumes rather than individual volumes, client devices placed in too close of a proximity for accurate differentiation could be grouped, with one device in a group acting as a BLE beacon.

Within the context of a home audio setup, it could be desirable to have multiple users have separate access to audio playback, from different client, at the same time. MPD and Mopidy can both be configure to run in multiple instances on the same device, with different ports. From these multiple audio server software instances, audio can be fed to Snapcast, which has the ability to be configured with multiple streams, from multiple inputs, which can be assigned by the useri [23].

# 7 Experimental Equipment and Procedures

## 7.1 Experimental Equipment Requirements

The following hardware equipment is required for testing of both the audio server software and the listener tracking implementations:

Experimental Equipment	
Description	Quantity
Raspberry Pi 3 Model B+	3
T5989DV - AC/DC Power Supply, 1 Output, 13 W, 5.1 V, 2.4 A	3
Adafruit I2S Audio Bonnet for Raspberry Pi - UDA1334A	3
SanDisk SDSDQAF3-008G-I	3
Audio Amplifier/Speaker Device (with Line In)	3

Table 7.1: Required Experimental Equipment

### Audio Server Software Equipment Requirements

In order to follow the testing steps outlined below in Section 7.2, three Raspberry Pi Model 3 B+ are required, along with three T5989DC AC/DC Power Supplies, three SanDisk Industrial 8GB Class 10 MicroSD cards, two Adafruit I2S Audio Bonnets, and two audio amplifier/speaker devices for audio output- This will allow for the client server streaming implementation between two Raspberry Pi's, with the third utilised for monitoring the devices used for streaming.

### Listener Tracking Equipment Requirements

In order to follow the testing steps outlined below in Section 7.2, three Raspberry Pi Model 3 B+ are required, along with three T5989DC AC/DC Power Supplies, three SanDisk Industrial 8GB Class 10 Micro SD cards, and one Android device. This will allow for the Bluetooth AltBeacons to be implemented on the Raspberry Pi's, with the Android device running the Bluetooth Beacon detection application.

## 7.2 Experimental Procedures

### Audio Server Software Testing Procedure

The testing steps outlined below will initiate playback of the available audio files from the audio server. Audio will be played for a total of six hours, divided amongst the three available audio formats, wave, FLAC, and MP3. As shown below, the three available albums

are “Hardwired To Self Destruct” by Metallica, in wave format, “Superfuzz Bigmuff” by Mudhoney in FLAC format, and “Sonic Highways” by Foo Fighters in MP3.

The Music Player Client “mpc” is used to control playback on each of the audio server softwares. The following mpc commands are used for playback configuration:

- ”add”
  - Adds the specified audio to the current playlist
- ”repeat”
  - Toggles the repeat option, or sets this option to the input argument, i.e. on or off
- ”play”
  - Begins playback of the current playlist
- ”stop”
  - Stops playback of the current playlist
- ”clear”
  - Clears all audio files from the current playlist

### **Testing Steps:**

The following test procedure must be followed in order to retrieve data for the comparison of the chosen audio server softwares.

1. Using ssh, connect to the audio server device
  - \$ ssh pi@<Server Pi IP>
2. Create a crontable on the server device to start and stop audio playback at a set time(s):
  - \$ crontab -e
    - Enter the following lines to the crontable
      - 00 10 \* \* \* mpc add Hardwired\_To-Self-Destruct\_BoxSet\_WAV/ && mpc repeat on && mpc play
      - 00 12 \* \* \* mpc stop && mpc clear && mpc repeat off
      - 02 12 \* \* \* mpc add mudhoney-superfuzz\_bigmuff-flac/ && mpc repeat on && mpc play
      - 02 14 \* \* \* mpc stop && mpc clear && mpc repeat off
      - 04 14 \* \* \* mpc add Sonic\_Highways/ && mpc repeat on && mpc play
      - 04 16 \* \* \* mpc stop && mpc clear && mpc repeat off

3. Once testing is complete of all available audio formats, replace the audio server software - "MPD" - with the "Mopidy" audio server software. Repeat step one for the "mopidy" server software.
4. Once testing is complete of all available audio formats, replace the audio server software - "Mopidy" - with the "Volumio" audio server software. Repeat step one for the "Volumio" server software.
5. Record the data output from Munin, available in the browser from <Munin Server IP>/munin.

For analysis, compare all applicable parameters as recorded from Munin. The results and analysis may be seen in Section 9.1.

### **Listener Tracking Testing Procedure**

The testing steps outlined below will test the ranging capabilities of three Bluetooth Beacons, as measured using an Android Smartphone. Three AltBeacons, running on Raspberry Pi 3 Model B+, are scanned for, with ranging requests done at distances of 1-5 meters at one meter intervals.

Nicolas Bridoux's "Beacon Scanner" Android application [24] is used in order to approximate the distance from the Android device to the AltBeacon, utilising bluetooth RSSI to estimate this distance. The following information may be taken from the application:

- "Beacon Type"
  - Returns the type of bluetooth beacon being used, e.g. iBeacon, Eddystone Beacon, and AltBeacon
- "Beacon ID"
  - The UUID for the beacon being used
- "RSSI"
  - The Received Signal Strength Indication from the bluetooth beacon to the Android device
- "TX"
  - The signal transmission strength from the bluetooth beacon

### **Testing Steps:**

The following test procedure must be followed in order to retrieve data for the ranging accuracy of the bluetooth beacons.

1. Using ssh, connect to the bluetooth beacon device.
  - \$ ssh pi@<Beacon Device IP>
2. Execute the AltBeacon script on the Raspberry Pi.

- \$ sudo ./altbeacon
3. Enable Bluetooth on the Android device.
  4. Run the Beacon Scanner application on the Android device.
  5. Place the Android device at a distance of 1m from the beacon device.
  6. Begin scanning for bluetooth devices.
  7. Record the estimated distance from the beacon device to the Android device.
  8. Repeat steps 5-7 for distances of 2, 3, 4, and 5 meters.

For analysis, compare all distance measured in the Beacon Scanner application with the actual distance. The results and analysis may be seen in Section 9.2.

# **8 Implementation and Testing**

## **8.1 Audio Server Software Implementation**

In order to execute the required testing of the audio server software, the following softwares must be installed on the server device, and the following configurations completed.

### **SSH**

SSH is a protocol used for end-to-end client-server secure connections [25]. SSH allows for remote login, and file transfers, from a client to a server device, i.e. from a development PC to an embedded Linux device. SSH utilises “keys” for authentication, and provides secure encryption between the client and server. Within this project, SSH is used in order to log in to, and run commands on the Raspberry Pi’s, which do not have a graphical desktop environment.

### **Munin**

Munin is a server performance monitoring software, which runs on an Apache server, with the client software running on each device requiring monitoring [26]. The recorded information is hosted on a locally accessible website, at the IP address of the server device. The output information is displayed in graphical representation, which can be analysed.

### **Cron**

Cron is a scheduling utility, which allows for the automation of command execution at specified times, or set time intervals [27]. Using a crontable, a file for entering cron jobs, the required testing schedule can be run on the audio server Raspberry Pi. For the purposes of testing the audio server software while streaming audio files of different formats, a crontable is configured to play audio in the Wave format, followed by audio in the FLAC format, followed by audio in the MP3 format. Each audio format is played continuously for two hours, with a two minute space between formats.

### **MPC**

MPC is the “Music Player Controller”, a software used for controlling MPD, or MPD derived softwares [28]. As such, it may be used to control MPD, Mopidy, and Volumio. Within the audio server software testing procedure, MPC is used in order to queue, play, and stop audio playback on each of the server configurations.

## Configurations

On the MPD server device, the configuration file, found at the location “/etc/mpd.conf” must be modified in order to output audio to the Snapcast server. The default “ALSA” output must first be deleted, and a new “FIFO” output must be added as follows:

Listing 8.1: MPD SnapServer Configuration

```
audio_output {
    type      "fifo"
    name     "my_pipe"
    path     "/tmp/snapfifo"
    format   "48000:16:2"
    mixer_type "software"
}
```

On the Mopidy server device, the configuration file, found at the location “/etc/mopidy/mopidy.conf” must be modified in order to output audio to the Snapcast server. The defualt audio output must be removed, with a new “filesink” output added as follows:

Listing 8.2: Mopidy SnapServer Configuration

```
[audio]
output = audioreample ! audioconvert !
audio/x-raw, rate=48000, channels=2, format=S16LE
! wavenc ! filesink location=/tmp/snapfifo
```

These audio outputs are used to feed audio to the Snapcast server, to be send via the network to the Snapcast client devices. The MPD configuration can also be used on the Volumio server, as Volumio utilises MPD and it’s configuration files for its audio playback.

## 8.2 Audio Server Software Testing

A number of parameters must be tested in order to determine the optimal open-source audio server solution. Each audio server software is tested under equal testing conditions, with the values for network usage, CPU temperature, CPU load, and CPU frequency monitored and recorded.

Testing setup consists of three Raspberry Pi’s, each running the Raspbian Stretch Light OS, with the exception of the Volumio server test configuration. One Raspberry Pi runs the audio server software, and the Snapcast server software. The second Raspberry Pi runs the Snapclient software. The final Raspberry Pi runs the Munin server software, allowing to monitor the clients, which are running on the other two Raspberry Pi’s. Both the audio server device and the Munin server device are connected to the network router/access point via Ethernet, with the client device connected to the network wirelessly.

Munin returns graphs of system parameters for the system being monitored. The graphs are divided into the categories of “Network”, “Processes”, “System”, and “Sensors”. The information contained in these graphs must be extracted, with the maximum, minimum, and average parameter values placed in a table for analysis.

## 8.3 Listener Tracking Implementation

In order to execute the required testing of the listener tracking, the following softwares must be installed, and the following configurations completed on the beacon devices, and the Android device.

### SSH

As described in Section 8.1, SSH allows for the remote login from a client device to a server device, allowing for commands to be run on the Raspberry Pi, sent from a client PC.

### BlueZ

BlueZ is the “Official Linux Bluetooth protocol stack” [29]. BlueZ provides a number of code examples for creating bluetooth beacons, using the AltBeacon protocol. These examples can be modified for the creation of AltBeacons with unique ID’s, and allow for the calibration of these beacons.

### Beacon Scanner Application

The Beacon Scanner android application allows for the monitoring and ranging of bluetooth beacons from an android device [24]. Utilising Bluetooth RSSI, the application estimates the distance from the Android device to the Bluetooth beacon. The device reports on beacon type, ID, RSSI, and Transmission power. These parameters allow for the identification and calibration of the beacon, along with the location determination for the client.

## 8.4 Listener Tracking Testing

In order to determine the accuracy and reliability of a Bluetooth Beacon, specifically the AltBeacon protocol, for the purposes of distance measurements in client tracking applications, a number of readings must be taken, at multiple distances from the beacon. This will show how the measured distance value changes with an increase in physical distance from beacon to scanning device.

Testing setup consists of three Raspberry Pi’s, each running the Raspbian Stretch Light OS, with an AltBeacon with a unique ID. The AltBeacons must be calibrated, by taking the RSSI value at 1 meter from the beacon device. The value is added into byte 29 of the AltBeacon, allowing for the beacon to more accurately provide ranging information. An Android device running the “Beacon Scanner” application is used to measure the RSSI value, and in turn to calculate an approximate distance to the beacon.

The distance results obtained from the execution of the testing steps outlined in Section 7.2 must be utilised to create tables of physical distance, estimated distance, and the deviation of the estimate from the actual distance. As such, these tables may be used in the analysis of the accuracy of bluetooth beacons in location determination.

# **9 Results and Analysis**

The following results and analysis have been completed following testing of the audio server softwares, and the client tracking, as described in Section 7.2.

## **9.1 Audio Server Software**

The following tables have been extracted from the data collected from Munin. A full list of results can be found within the Appendices Section 12.2. The client and server data has been combined under the headings of Network, System, and Sensors, for each of the audio server software solutions.

### **MPD**

The network information for the MPD Server and SnapClient configuration below shows there are no Ethernet errors or traffic on the Client device, as it is connected to the network via WiFi. Conversely, on the Server device, there are Wireless network errors, and traffic values, as the server device is both setup on the network via WiFi and Ethernet.

Network						
Eth0 Errors (Client)						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	0.00	0.00	0.00	0.00	0.00	0.00
Collisions	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Errors (Server)						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	830.03m	0.00	835.49m	0.00	853.19m	0.00
Collisions	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Traffic (Client)						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Traffic (Server)						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	1.25k	1.31k	23.66k	951.47k	29.07k	1.27M
Wlan0 Errors (Client)						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	270.53m	0.00	302.72m	0.00	343.80m	0.00
Collisions	0.00		0.00		0.00	
Wlan0 Errors (Server)						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	327.00m	0.00	335.22m	0.00	349.93m	0.00
Collisions	0.00		0.00		0.00	
Wlan0 Traffic (Client)						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	669.92	1.58k	939.62k	31.80k	1.26M	39.03k
Wlan0 Traffic (Server)						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	186.42	17.12	321.71	22.45	741.32	39.21

Table 9.1: MPD Server and SnapClient Device Network Parameters

Within the Munin system measurements, it can be seen that on the Server device, approximately 964MB of the 1GB of DDR2 RAM on the Raspberry Pi Model 3B+ is in use on average, with average system load of 0.41, and CPU usage of 5.89% (idling at 92% - Note: The Munin monitoring software measures CPU usage percentage from 0-400%, i.e. usage on each CPU core). On the Client device, approximately 327MB of the 1GB of DDR2

RAM is in use on average, with average system load of 0.13, and CPU usage of 3.35% (idling at 96%)

System			
<b>Load Average (Client)</b>			
	Min	Avg	Max
Load	0.02	0.13	0.46
<b>Load Average (Server)</b>			
	Min	Avg	Max
Load	0.03	0.41	1.03
<b>Memory Usage (Bytes) (Client)</b>			
	Min	Avg	Max
Active	164.04M	165.38M	167.67M
Inactive	51.14M	51.17M	51.21M
Unused	670.26M	673.18M	675.15M
<b>Memory Usage (Bytes) (Server)</b>			
	Min	Avg	Max
Active	270.40M	408.59M	437.63M
Inactive	424.17M	541.23M	589.36M
Unused	31.03M	35.88M	43.78M
<b>CPU Usage (%) (Client)</b>			
	Min	Avg	Max
System	1.05	3.35	9.27
Idle	381.73	384.41	394.69
<b>CPU Usage (%) (Server)</b>			
	Min	Avg	Max
System	1.21	5.89	15.08
Idle	363.71	369.60	394.16

Table 9.2: MPD Server and SnapClient Device System Parameters

The Raspberry Pi CPU frequency and temperature were measured using a Munin plugin. The Client device kept an average frequency of 600MHz, with average frequency scaling of 618.10MHz on CPU core 1 and 2, and average frequency scaling of 610.10MHz on CPU core 3 and 4. The average temperature of the Client device is 42.66 °C.

The Server device had an average frequency of 656.53MHz, however at times reached its maximum frequency of 1.4GHz. On CPU cores 1-4 the average frequency scaling is 691.30MHz, and had an average temperature of 56.11 °C.

Sensors			
<b>CPU Frequency (MHz) (Client)</b>			
	Min	Avg	Max
CPU	600.00	600.00	600.00
<b>CPU Frequency (MHz) (Server)</b>			
	Min	Avg	Max
CPU	600.00	656.53	1.40k
<b>CPU Frequency Scaling (MHz) (Client)</b>			
	Min	Avg	Max
CPU1	613.87	618.10	620.98
CPU2	613.92	618.10	620.97
CPU3	613.87	610.10	620.99
CPU4	613.92	610.10	620.98
<b>CPU Frequency Scaling (MHz) (Server)</b>			
	Min	Avg	Max
CPU1	624.32	691.30	842.15
CPU2	624.32	691.30	842.12
CPU3	624.30	691.30	842.14
CPU4	624.30	691.30	842.11
<b>CPU Temperature (°C) (Client)</b>			
	Min	Avg	Max
CPU	41.86	42.66	44.00
<b>CPU Temperature (°C) (Server)</b>			
	Min	Avg	Max
CPU	53.69	56.11	58.52

Table 9.3: MPD Server and SnapClient Device Sensor Parameters

## Mopidy

The network information for the Mopidy Server and SnapClient configuration below, again, shows that there are no Ethernet errors or traffic on the Client device, due to the network connection being wireless. The Server device has both wireless and wired errors and traffic.

Network						
Eth0 Errors (Client)						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	0.00	0.00	0.00	0.00	0.00	0.00
Collisions	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Errors (Server)						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	827.43m	0.00	835.03m	0.00	852.73m	0.00
Collisions	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Traffic (Client)						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Traffic (Server)						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	1.23k	1.34k	25.65k	961.24k	35.72k	1.34M
Wlan0 Errors (Client)						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	313.56m	0.00	330.82m	0.00	344.32m	0.00
Collisions	0.00		0.00		0.00	
Wlan0 Errors (Server)						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	329.11m	0.00	334.61m	0.00	347.44m	0.00
Collisions	0.00		0.00		0.00	
Wlan0 Traffic (Client)						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	181.87	17.17	280.87	22.18	756.88	31.00
Wlan0 Traffic (Server)						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	636.24	1.58k	950.23k	34.74k	1.33M	48.40k

Table 9.4: Mopidy Server and SnapClient Device Network Parameters

In the system measurements, the Server device uses approximately 950MB of RAM on average, with average system load on 0.23, and average CPU Usage of 3.64%. The Client device uses on average approximately 338MB of RAM, with average system load of 0.11, and CPU usage of 3.43% on average.

System			
<b>Load Average (Client)</b>			
	Min	Avg	Max
Load	0.02	0.11	0.26
<b>Load Average (Server)</b>			
	Min	Avg	Max
Load	0.05	0.23	0.40
<b>Memory Usage (Bytes) (Client)</b>			
	Min	Avg	Max
Active	170.56M	171.03M	171.55M
Inactive	56.72M	56.77M	56.81M
Unused	661.03M	661.75M	662.69M
<b>Memory Usage (Bytes) (Server)</b>			
	Min	Avg	Max
Active	161.88M	375.25M	445.90M
Inactive	245.70M	462.17M	701.93M
Unused	26.69M	54.62M	472.22M
<b>CPU Usage (%) (Client)</b>			
	Min	Avg	Max
System	1.01	3.43	9.45
Idle	381.26	384.85	394.51
<b>CPU Usage (%) (Server)</b>			
	Min	Avg	Max
System	1.68	3.64	7.53
Idle	351.52	365.23	386.77

Table 9.5: Mopidy Server and SnapClient Device System Parameters

The CPU frequency of the Client device is on average 608.89MHz, with an average of 616.29 frequency scaling on all four CPU cores. The CPU temperature on the Client device has an average value of 44.63 °C.

The CPU frequency of the Server device kept, on average, at the maximum frequency of 1.4GHz, with all four CPU cores frequency scaling at 646.91MHz, and average temperature of 58.94 °C.

Sensors			
<b>CPU Frequency (MHz) (Client)</b>			
	Min	Avg	Max
CPU	600.00	608.89	1.37k
<b>CPU Frequency (MHz) (Server)</b>			
	Min	Avg	Max
CPU	1.40k	1.40k	1.40k
<b>CPU Frequency Scaling (MHz) (Client)</b>			
	Min	Avg	Max
CPU1	611.73	616.29	620.02
CPU2	611.73	616.29	620.02
CPU3	611.73	616.29	620.02
CPU4	611.73	616.29	620.02
<b>CPU Frequency Scaling (MHz) (Server)</b>			
	Min	Avg	Max
CPU1	638.58	646.91	674.50
CPU2	638.58	646.91	674.50
CPU3	638.58	646.91	674.50
CPU4	638.58	646.91	674.50
<b>CPU Temperature (°C) (Client)</b>			
	Min	Avg	Max
CPU	43.48	44.63	46.14
<b>CPU Temperature (°C) (Server)</b>			
	Min	Avg	Max
CPU	56.93	58.94	60.15

Table 9.6: Mopidy SnapClient Device Sensor Parameters

## Volumio

The network information for the Volumio Server and SnapClient configuration below, again, shows that there are no Ethernet errors or traffic on the Client device, due to the network connection being wireless. The Server device has both wireless and wired errors and traffic.

Network						
Eth0 Errors (Client)						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	0.00	0.00	0.00	0.00	0.00	0.00
Collisions	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Errors (Server)						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	826.87m	0.00	835.74m	0.00	856.40m	0.00
Collisions	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Traffic (Client)						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Traffic (Server)						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	15.75k	1.75k	38.40k	1.01M	44.88k	1.34M
Wlan0 Errors (Client)						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	304.44m	0.00	332.58m	0.00	342.16m	0.00
Collisions	0.00		0.00		0.00	
Wlan0 Errors (Server)						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	0.00	0.00	0.00	0.00	0.00	0.00
Collisions	0.00		0.00		0.00	
Wlan0 Traffic (Client)						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	631.61	1.60k	993.84k	31.64k	1.32M	39.29k
Wlan0 Traffic (Server)						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	0.00	0.00	2.30	3.69	13.02	20.92

Table 9.7: Volumio Server and SnapClient Device Network Parameters

Within the System measurements, it can be seen that the Server device uses on average 965MB of the 1GB of available RAM, has average load of 0.11. The Server device has approxiamtely 2.61% CPU Usage on average.

The Client device uses, on average, 224MB of the available 1GB of RAM, and has system

load of 0.14 on average. The Client device averages approximately 4.07% CPU Usage.

System			
<b>Load Average (Client)</b>			
	Min	Avg	Max
Load	0.01	0.14	0.34
<b>Load Average (Server)</b>			
	Min	Avg	Max
Load	0.02	0.11	0.23
<b>Memory Usage (Bytes) (Client)</b>			
	Min	Avg	Max
Active	92.55M	93.46M	94.27M
Inactive	30.49M	30.54M	30.58M
Unused	774.41M	775.71M	777.38M
<b>Memory Usage (Bytes) (Server)</b>			
	Min	Avg	Max
Active	508.26M	525.56M	596.66M
Inactive	296.90M	364.93M	374.74M
Unused	30.66M	36.30M	47.90M
<b>CPU Usage (%) (Client)</b>			
	Min	Avg	Max
System	1.14	4.07	10.54
Idle	381.29	384.25	394.36
<b>CPU Usage (%) (Server)</b>			
	Min	Avg	Max
System	1.50	2.61	3.06
Idle	378.43	382.80	395.45

Table 9.8: Volumio Server and SnapClient Device System Parameters

Within Munins Sensor measurements, it can be seen that the average CPU frequency of the Client device is 1.39GHz with average frequency scaling of 627.54MHz on all four CPU cores. The client device had an average temperature of 45.65 °C.

The Server device's CPU frequency kept at it's maximum value of 1.4GHz, with the average frequency scaling on all four CPU cores also averaging at 1.4GHz. The CPU temperature of the Server device averaged at 59.97 °C.

Sensors			
<b>CPU Frequency (MHz) (Client)</b>			
	Min	Avg	Max
CPU	613.33	1.39k	1.40k
<b>CPU Frequency (MHz) (Server)</b>			
	Min	Avg	Max
CPU	1.40k	1.40k	1.40k
<b>CPU Frequency Scaling (MHz) (Client)</b>			
	Min	Avg	Max
CPU1	621.70	627.54	631.72
CPU2	621.70	627.54	631.72
CPU3	621.72	627.54	631.72
CPU4	621.72	627.54	631.70
<b>CPU Frequency Scaling (MHz) (Server)</b>			
	Min	Avg	Max
CPU1	1.40k	1.40k	1.40k
CPU2	1.40k	1.40k	1.40k
CPU3	1.40k	1.40k	1.40k
CPU4	1.40k	1.40k	1.40k
<b>CPU Temperature (°C)(Client)</b>			
	Min	Avg	Max
CPU	44.55	45.65	47.23
<b>CPU Temperature (°C) (Server)</b>			
	Min	Avg	Max
CPU	58.53	59.97	60.69

Table 9.9: Volumio Server and SnapClient Device Sensor Parameters

## Audio Server Software Analysis

From the results in Table 9.1, Table 9.4, Table and 9.7 it can be seen that the Mopidy Audio Server experienced the least Ethernet drops, and the most outbound Ethernet Traffic (with the same value as Volumio). The Mopidy server also had the highest WLAN Traffic. The difference in Ethernet drops experienced by each of the server options is minimal, with the MPD server having an average value of  $835.49m$ , the Mopidy server having an average value of  $835.03m$ , and the Volumio having an average value of  $835.74m$ . There is variation in the output packets from the Ethernet traffic measurements between each Server. The MPD server has an average value of  $951.47k$  packets sent, the Mopidy server has an average value of  $961.24k$  packets sent, and the Volumio server has an average value of  $1.01M$  packets sent. A large difference can be seen in the WLAN traffic between the server options. The MPD server has an average value of 22.45 packets sent, the Mopidy server has an average value of  $34.74k$  packets sent, and the Volumio server has an average value of 3.69 packets sent.

From the results in Table 9.2, Table 9.5, and Table 9.8, it can be seen that the highest system load was experienced by the MPD audio server, with an average value of 0.41, and a maximum value of 1.03. The Mopidy and Volumio Server had an average load of 0.23 and 0.11 respectively, with maximum values of 0.40 and 0.23 respectively. The memory usage of the Mopidy server was the lowest, with an average value of  $945.38MB$ , and a maximum usage of approximately  $973.31MB$ . The MPD and Volumio Servers had an

average memory usage of  $964.12MB$  and  $963.70MB$ , with maximum values of  $968.97MB$  and  $969.34MB$  respectively. The Volumio Server experienced the lowest CPU usage, with system usage averaging  $2.61\%$ , and a maximum value of  $3.06\%$ . The MPD and Mopidy Servers had system CPU Usage values of  $5.89\%$  and  $3.64\%$ , with maximum values of  $15.08\%$  and  $7.53\%$  respectively.

From the results in Table 9.3, Table 9.6, Table 9.9 it can be seen that the lowest average CPU frequency, temperature, and CPU frequency scaling were achieved by the MPD server. This server had an average CPU frequency of  $656.53MHz$ , average CPU frequency scaling of  $691.30MHz$ , and average CPU temperature of  $56.11^{\circ}C$ . The Mopidy and Volumio Servers had average CPU frequency values of  $1.4GHz$ , with average frequency scaling values of  $646.91MHz$  and  $1.4GHz$  respectively. The low CPU frequency value of the MPD Server device can be attributed to a number of issues, such as thermal throttling, however, due to idling, the device can also lower CPU frequency to  $600MHz$  [30].

While streaming, there were no noticeable audio issues detected. It can be seen in the case of all audio server softwares, Section 12.1, the highest network throughput occurs for files of the WAV format, followed by MP3. The lowest network throughput is experienced by audio in the FLAC format. Audio played from both the audio serving device, and the client device, streamed via Snapcast, with no “popping” or audio distortion experienced. As the performance of audio playback was not varying during testing, and due to the minimal differences between the server softwares, it is concluded that, due to ease of configuration, and lowest memory usage and CPU temperatures, along with comparable Network and System measurement values, the MPD server was chosen as the Server software to be used.

## 9.2 Listener Tracking

The following tables are the outcome of the testing described in Section 7.2, Listener Tracking Testing Procedure. The distance estimates from the Android device to the three calibrated Raspberry Pi AltBeacons are listed, alongside the actual distance measurements.

### Server Device Beacon

Bluetooth Distance Measurements (m)		
Distance Measurement	BLE Distance Estimate	Deviation
1	0.97	0.03
2	2.44	-0.44
3	3.19	-0.19
4	3.62	0.38
5	4.54	0.46

Table 9.10: Server Device Beacon Bluetooth Distance Measurements

As seen in Table 9.10, there is a deviation in the distance estimate of  $0.03m$  at  $1m$ ,  $0.44m$  at  $2m$ ,  $0.19m$  at  $3m$ ,  $0.38m$  at  $4m$ , and  $0.46m$  at  $5m$ .

## “Client1” Device Beacon

Bluetooth Distance Measurements (m)		
Distance Measurement	BLE Distance Estimate	Deviation
1	0.98	0.02
2	1.34	0.66
3	2.16	0.84
4	1.35	2.65
5	2.40	2.60

Table 9.11: ”Client1” Device Beacon Bluetooth Distance Measurements

As seen in Table 9.11, there is a deviation in the distance estimate of 0.02m at 1m, 0.66m at 2m, 0.84m at 3m, 2.65m at 4m, and 2.60m at 5m.

## “Client2” Device Beacon

Bluetooth Distance Measurements (m)		
Distance Measurement	BLE Distance Estimate	Deviation
1	1.16	-0.16
2	2.21	-0.21
3	2.89	0.11
4	4.18	-0.18
5	5.34	-0.34

Table 9.12: ”Client2” Device Beacon Bluetooth Distance Measurements

As seen in Table 9.12, there is a deviation in the distance estimate of 0.16m at 1m, 0.21m at 2m, 0.11m at 3m, 0.18m at 4m, and 0.34m at 5m.

From the results obtained from testing, it can be seen that there is a maximum deviation of 2.65 meters, with a minimum deviation of 0.02 meters. There is an average deviation of 0.618 meters. There is no direct correlation between increases in physical distance, and increases in the BLE distance estimate visible from the captured data. More thorough testing would be required in order to more accurately determine the accuracy of the BLE distance estimates. From the obtained results however, it can be seen that a minimum accuracy of within 2 meters may be achieved, which is sufficient for movement within a home environment. This, in addition to the multiple measurements being taken, will allow for greater accuracy, with outlier values being able to be discarded from measurements.

# 10 Ethics

## 10.1 Audio Tracks

While there have been questions raised in recent years over the ethical problems with streaming services, and the revenue paid to artists whose music is played via their platforms, there are also a number of issues with audio piracy from users illegally downloading audio tracks. As solutions such as the one provided by this project offer both options for both streaming and locally stored audio, these ethical issues must be explored in order to determine the impact that a solution such as this may have.

### Streaming Solutions

With the large increase in paying subscribers in audio streaming services, such as Spotify, in the last number of years questions have arisen with regards to the payment received by artists. Spotify, which, as of 2018 [4] is the largest audio streaming service, with a paying subscriber count of approximately 96 million as of Q4 2018 [31], as displayed in Figure 10.1, has been criticized for the payment which the artists on its service receive. More popular artists, who hold a larger percentage of the rights to their music can earn between \$0.006 and \$0.0084 per stream. Studies have shown that per million plays, an artist generates approximately \$7,000 on Spotify, or approximately \$1,650 on Pandora [32].

While Spotify and other streaming services may provide users with unprecedented access to audio, it has been noted that the effect it has had on audio track sales could be a detriment to artist income. A paper co-authored by Spotify's Director of Economics has examined the “pro-rata” model used by Spotify to distribute subscriber income, which is based on an artists percentage of total track plays, concluding that a pro-rata model is beneficial to artists over a user-centric model when, in the case of \$70 million distributable income, increasing system costs exceed 4.64% [33].

Conversely, a 2017 paper from Digital Media Finland explores the benefits of the user-centric system [34]. This study shows that in the “pro-rata” model, individual user habits are not accounted for, with subscription income distributed across all tracks played. In a “user-centric” model, the subscription income is distributed across all of the tracks played by the user. This is beneficial to artists of less popular genres, giving their listeners the opportunity to support the artists they listen to, without placing their money in a pot for distribution.

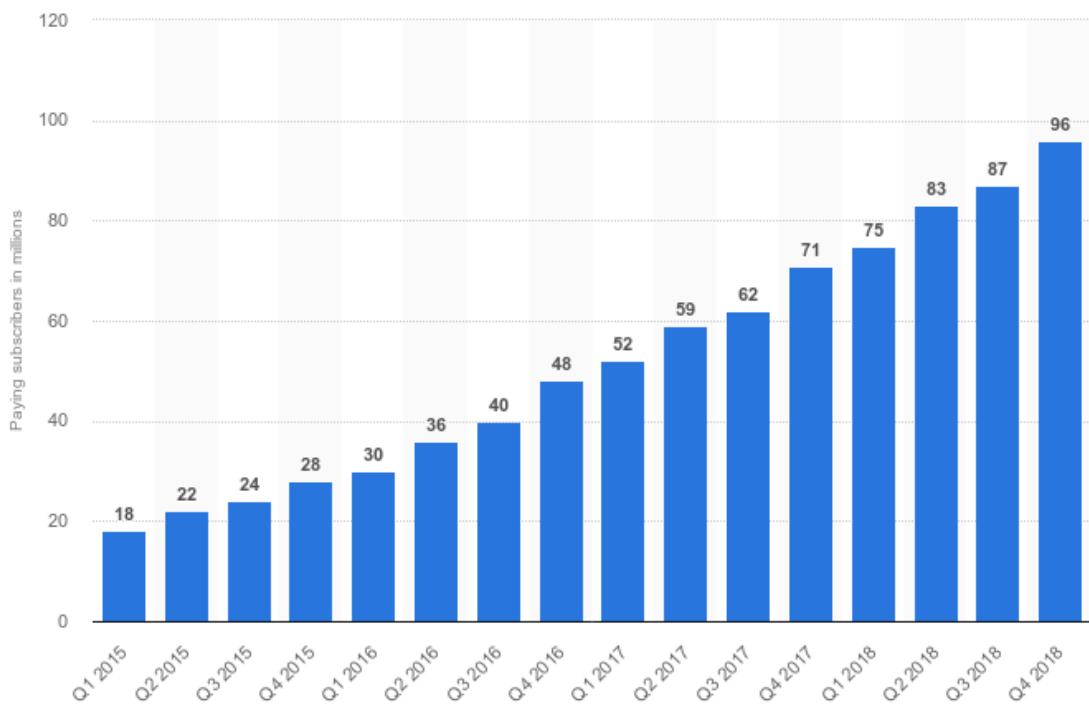


Figure 10.1: Spotify Paying Subscribers in Millions from Q1 2015 to Q4 2018

With the significant increase in spending on streaming service subscriptions over physical media sales, and digital downloads, as in Figure 10.2, the fair and equal payment of artists must be considered. Artists of more niche genres can be negatively affected by the currently used “pro-rata” models, however, the change to a “user-centric” model may not benefit these artists, as they increase the processing costs at the side of the streaming service. As such, care must be taken to ensure that artists incomes are not so negatively affected so as to reduce the number of smaller artists within the industry.

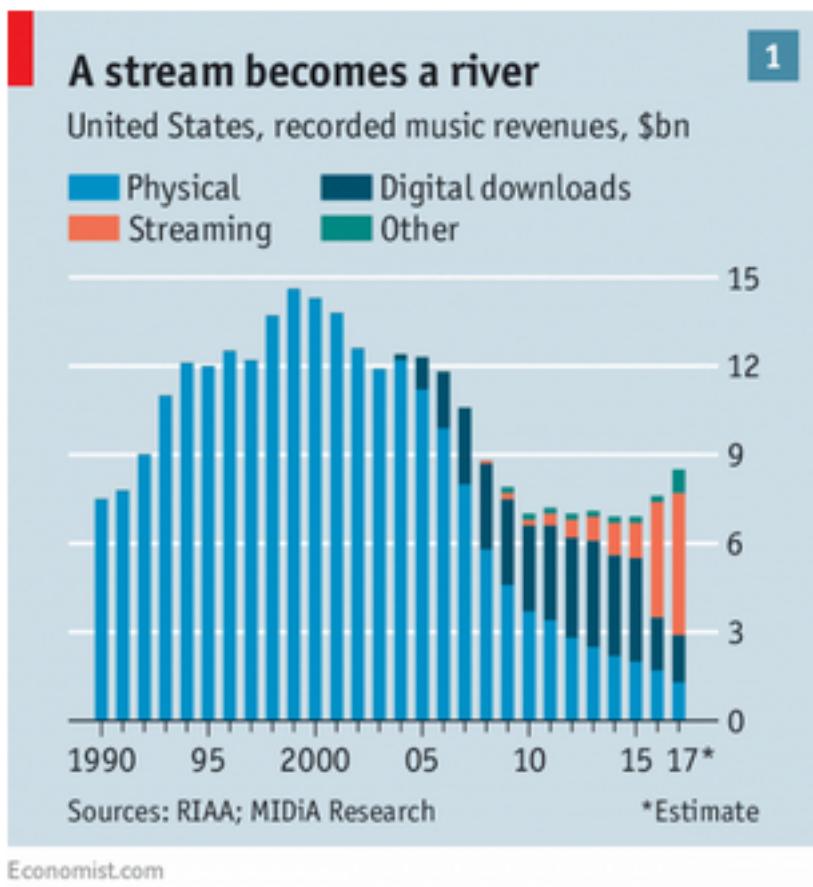


Figure 10.2: Recorded Music Revenues for the United States [4]

## Audio Piracy

When considering solutions which use locally stored audio, the ethical issue of sourcing these audio tracks must be discussed. While it may be presumed that, with the increase in the availability of audio streaming, audio piracy would significantly decrease, it has been noted that audio piracy affects physical and digital media consumption [35]. While the Global Online Piracy Study [35] suggests that audio piracy is decreasing, MUSO, a company aiming to study and solve issues with audio piracy, has stated in their annual piracy report a 1.6% increase in global piracy in 2017 [36]. Joost and Quintais however contest these figures, noting that MUSO “overestimate the number of and visits to pirate websites” [35].

While piracy via illegal downloads seems to be decreasing, only replacing the declining digital and physical sales [4], illegal streaming via personal licences being used in place of business licences may be a more prominent issue, with a survey showing 83% of small business owners use a personal streaming service account in their premises [37].

Sourcing audio files from legal sources, such as physical or online retailers, is important in order to ensure proper payment is received by artists and production companies. The use of locally stored audio in this project may however increase the use of pirated audio, due to a lack of accessibility to these physical or digital media.

## 10.2 Listener Tracking

Mobile tracking has a number of ethical implications, imposing on an individuals right to privacy. Access to a users location data must be privileged, accessible only when necessary, and only from the application requiring the data. Bluetooth beacons, as used within this project, have the capacity for two-way communication. As such, there is the concern of the information being intercepted, which could lead to malicious use of the captured data [38].

As proximity based services become more common, it becomes increasingly important to ensure the protection of a users personal data, and location information. Both the Apple App Store, and Google Play Store require that any application which requires access to location services, or to bluetooth services request permission from the user to access these services. This allows users the ability to block applications accessing this information. Furthermore, laws have been introduced prohibiting companies from using personal data from non-consenting users [39]. Transparency is required throughout the privacy policies of applications and services, in order to correctly inform users of the data being accessed, and the storage and usage conditions of this data.

# **11 Conclusions and Recommendations**

## **11.1 Conclusions**

## **11.2 Recommendations**

# 12 Appendix

## 12.1 Audio Server Software Munin Data

### MPD

#### Disk



Figure 12.1: MPD Disk I/O on Client and Server Device

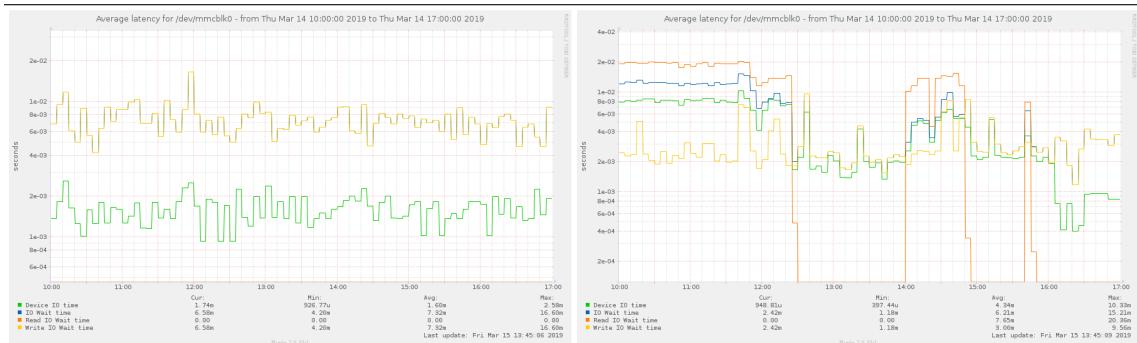


Figure 12.2: MPD Client and Server Device Disk Latency

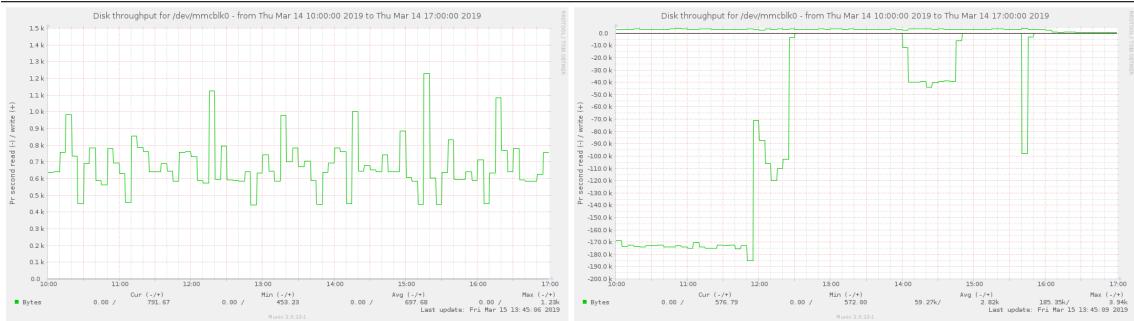


Figure 12.3: MPD Client and Server Device Disk Throughput

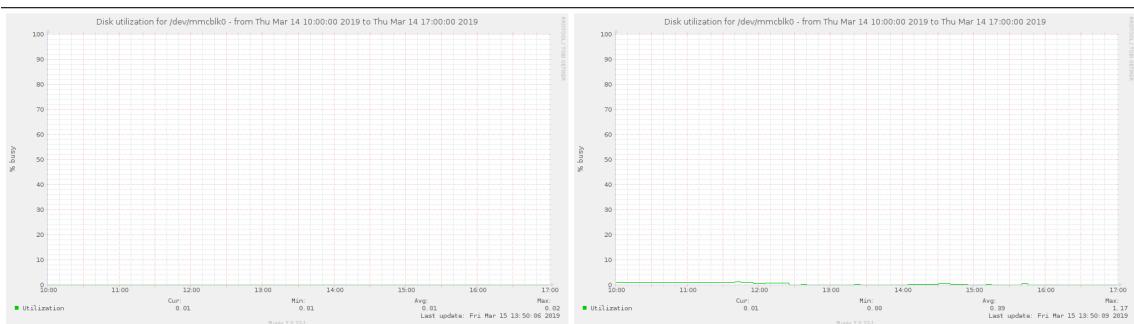


Figure 12.4: MPD Client and Server Device Disk Utilization

## Network

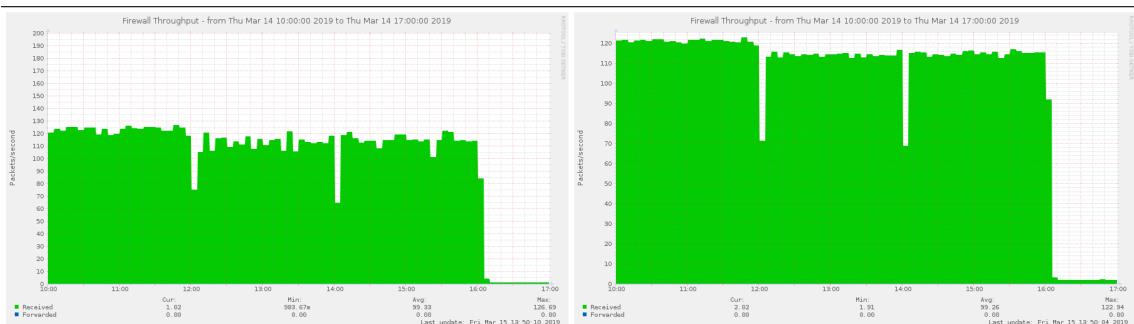


Figure 12.5: MPD Client and Server Device Firewall Throughput

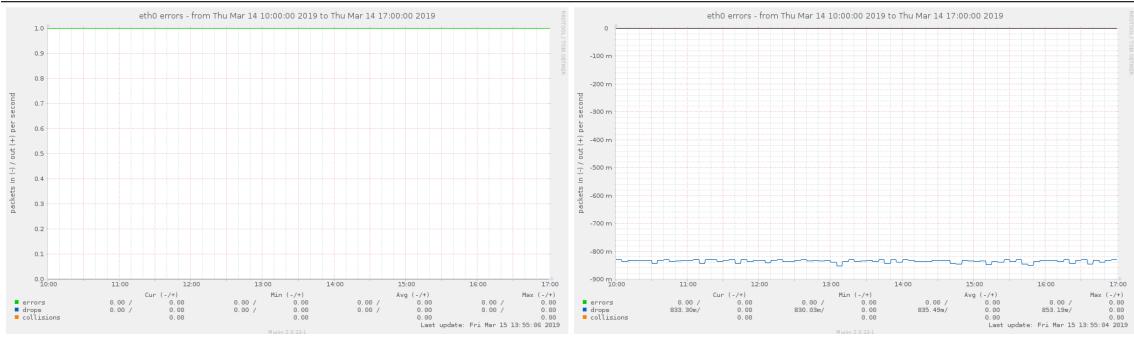


Figure 12.6: MPD Client and Server Device Eth Errors

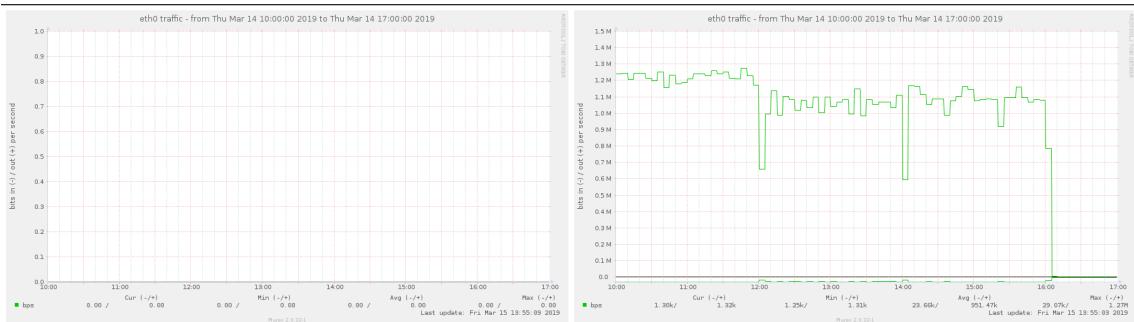


Figure 12.7: MPD Client and Server Device Eth Traffic

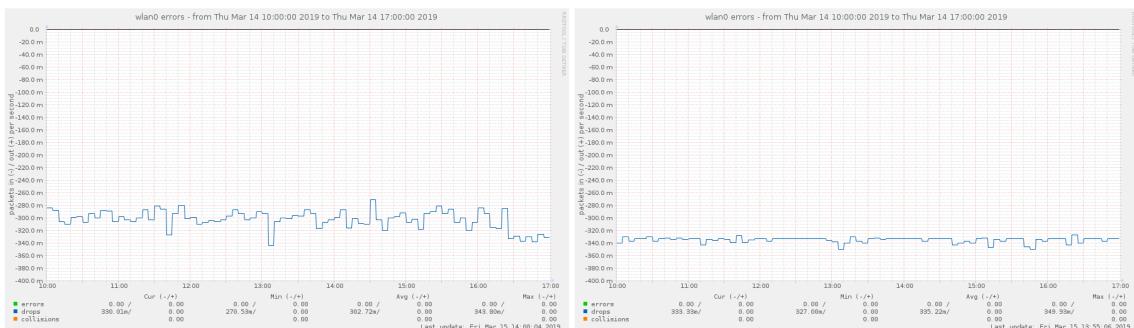


Figure 12.8: MPD Client and Server Device Wlan Errors

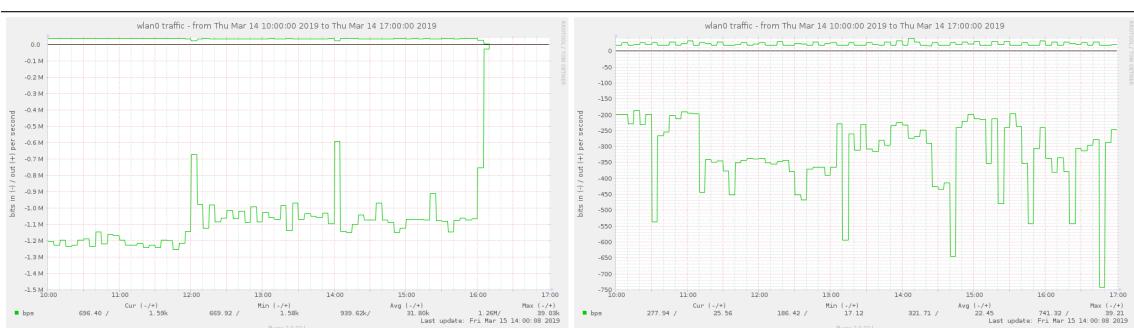


Figure 12.9: MPD Client and Server Device Wlan Traffic



Figure 12.10: MPD Client and Server Device Netstat

## Processes

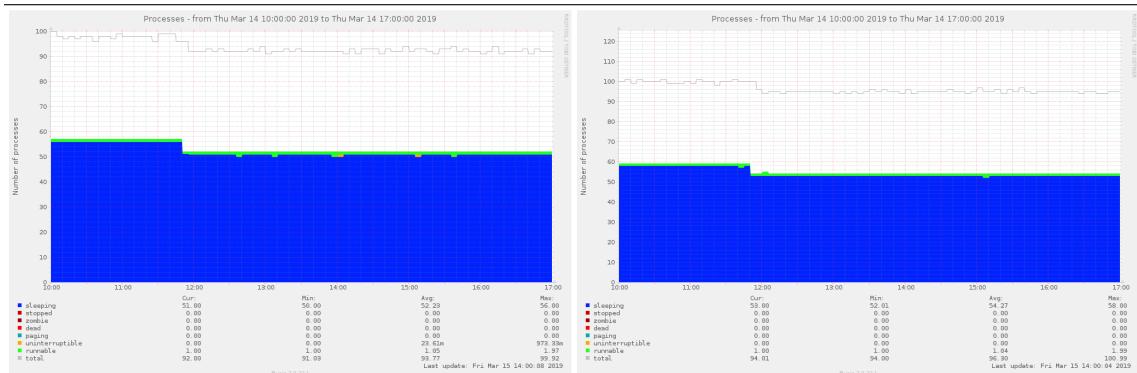


Figure 12.11: MPD Client and Server Device Processes

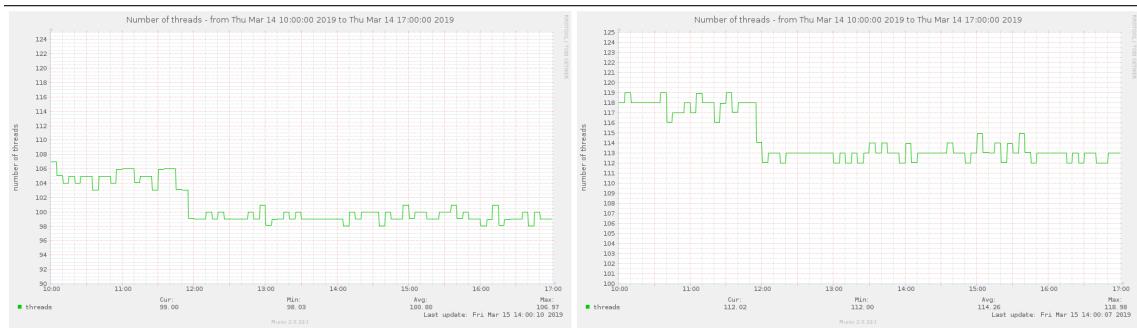


Figure 12.12: MPD Client and Server Device Number of Threads

## System

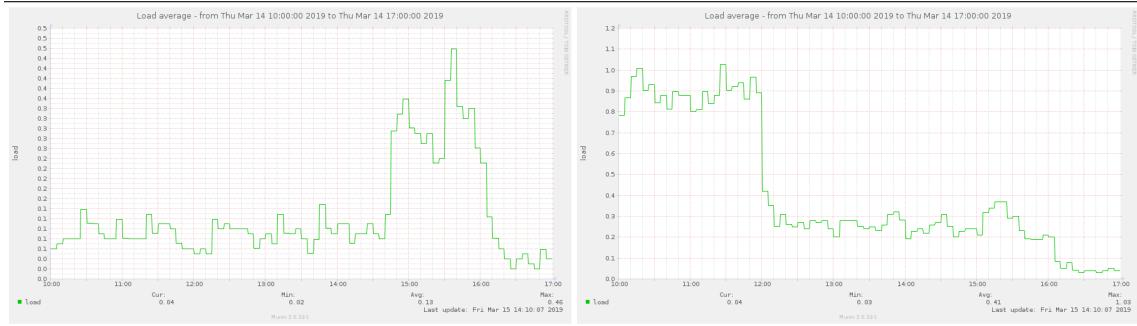


Figure 12.13: MPD Client and Server Device Load Average



Figure 12.14: MPD Client and Server Device Individual Interrupts

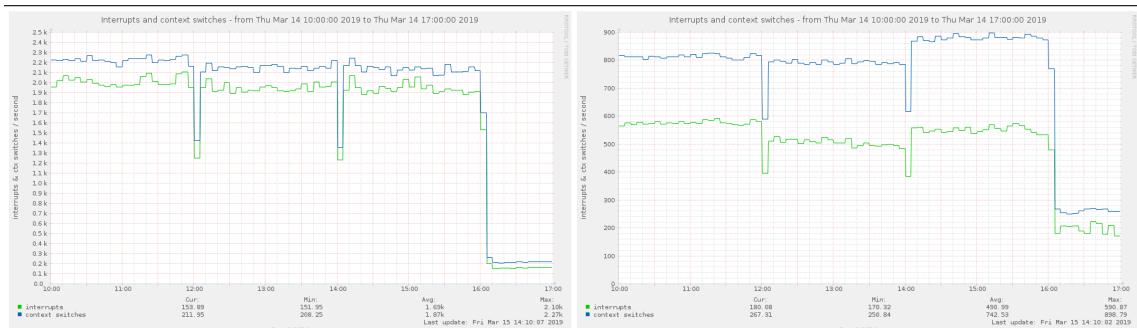


Figure 12.15: MPD Client and Server Device Interrupts and Context Switches

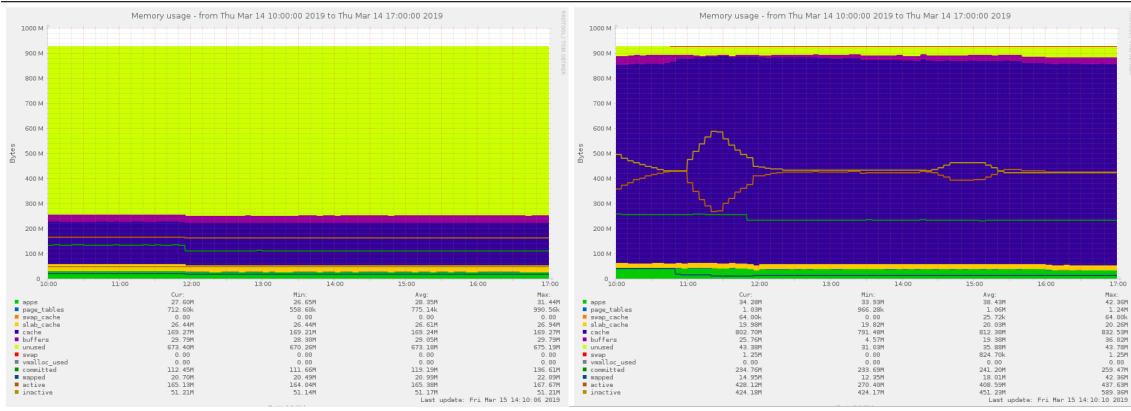


Figure 12.16: MPD Client and Server Device Memory Usage



Figure 12.17: MPD Client and Server Device Fork Rate



Figure 12.18: MPD Client and Server Device CPU Usage

## Sensors

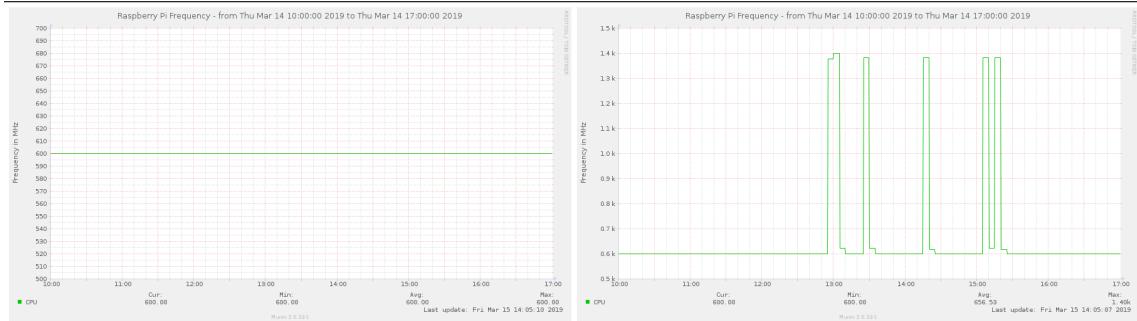


Figure 12.19: MPD Client and Server Device CPU Frequency

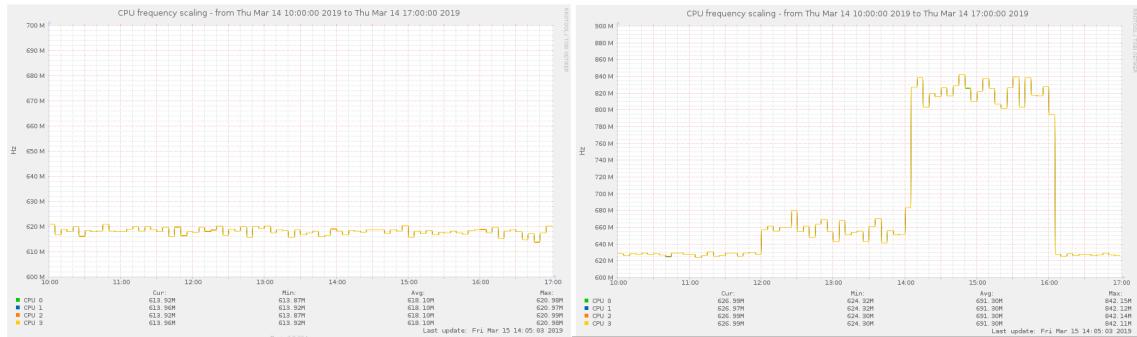


Figure 12.20: MPD Client and Server Device CPU Frequency Scaling

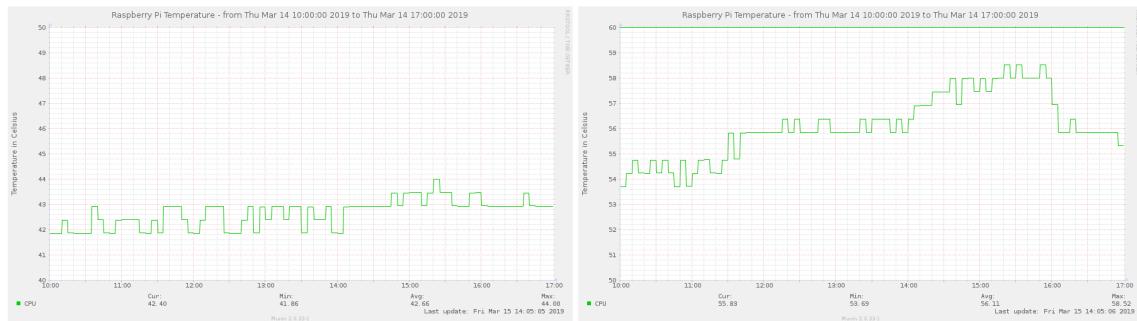


Figure 12.21: MPD Client and Server Device CPU Temperature

## Mopidy

### Disk

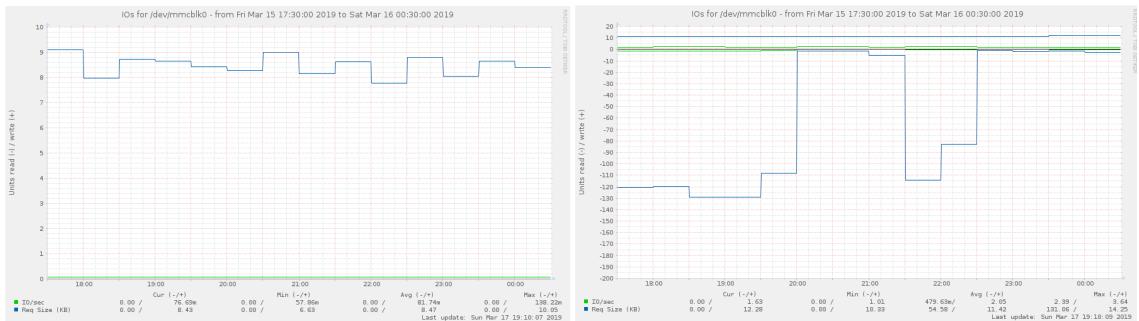


Figure 12.22: Mmopidy Disk I/O on Client and Server Device



Figure 12.23: Mopidy Client and Server Device Disk Latency

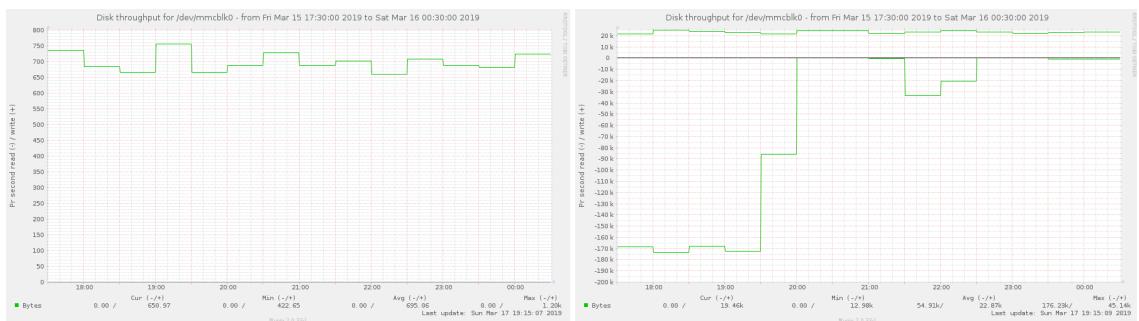


Figure 12.24: Mopidy Client and Server Device Disk Throughput

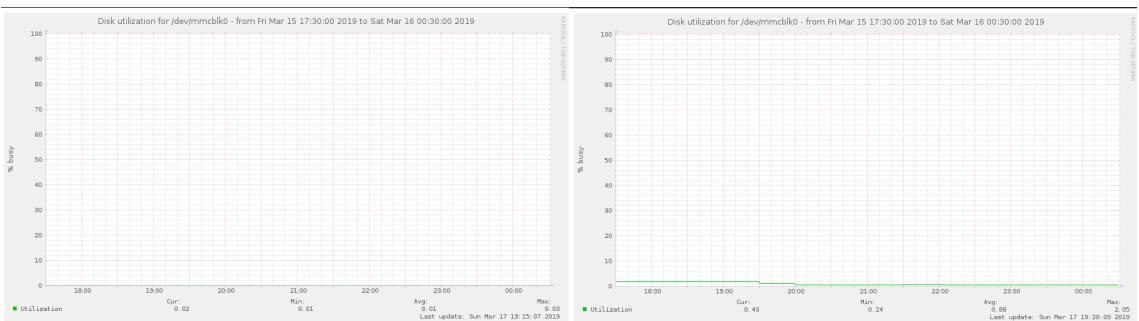


Figure 12.25: Mopidy Client and Server Device Disk Utilization

## Network

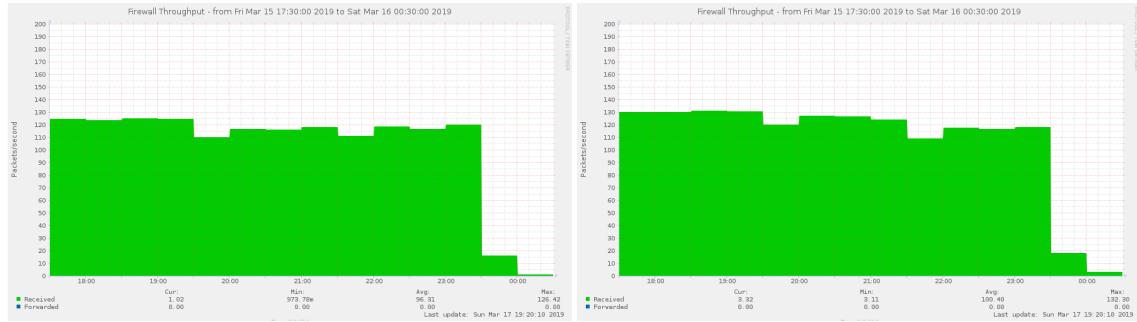


Figure 12.26: Mopidy Client and Server Device Firewall Throughput



Figure 12.27: Mopidy Client and Server Device Eth Errors

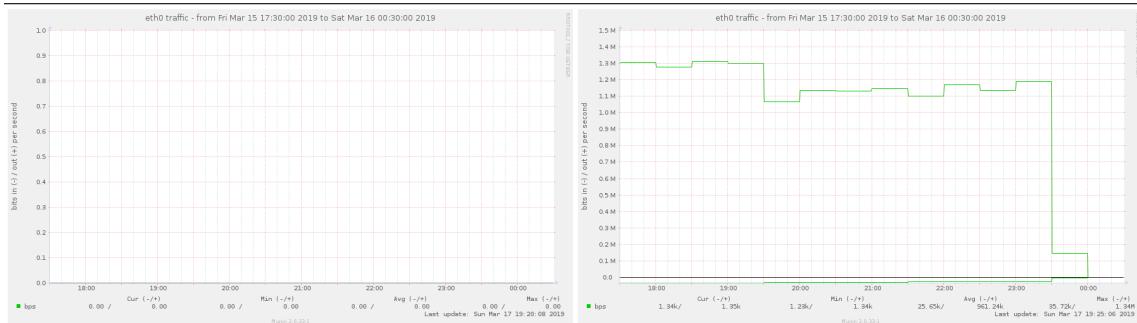


Figure 12.28: Mopidy Client and Server Device Eth Traffic

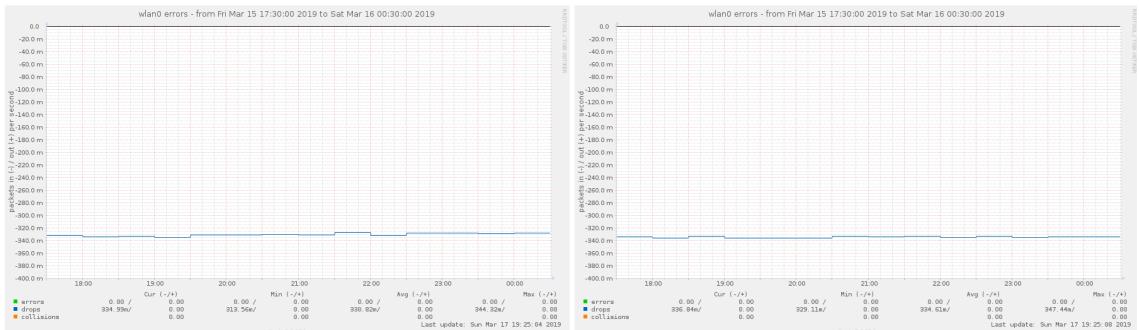


Figure 12.29: Mopidy Client and Server Device Wlan Errors

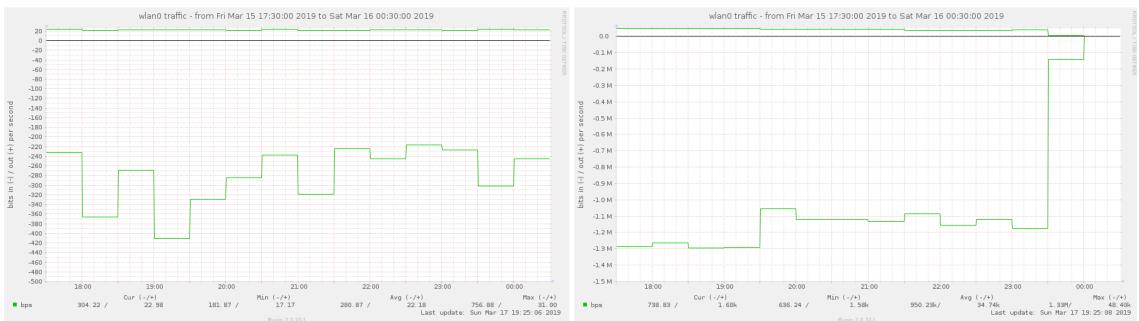


Figure 12.30: Mopidy Client and Server Device Wlan Traffic



Figure 12.31: Mopidy Client and Server Device Netstat

## Processes

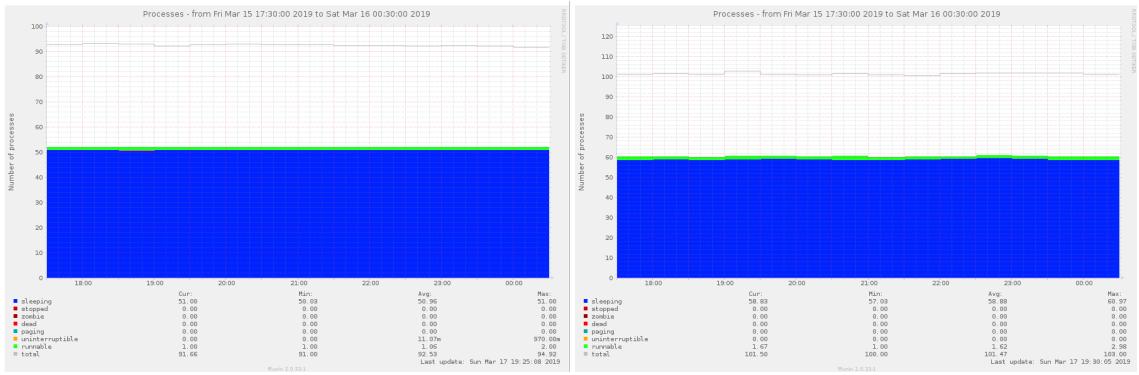


Figure 12.32: Mopidy Client and Server Device Processes

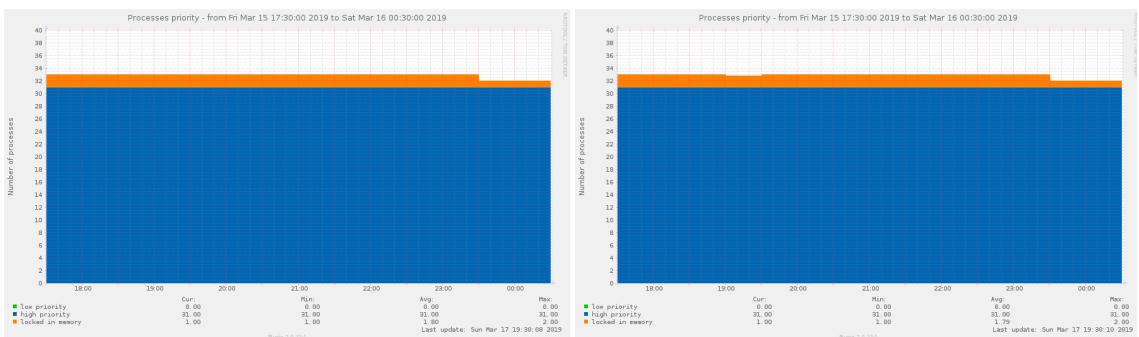


Figure 12.33: Mopidy Client and Server Device Process Priority

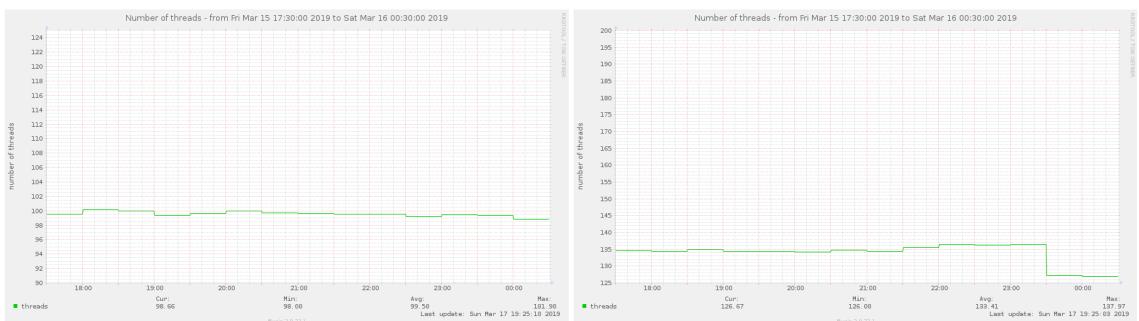


Figure 12.34: Mopidy Client and Server Device Number of Threads

## System



Figure 12.35: Mopidy Client and Server Device Load Average

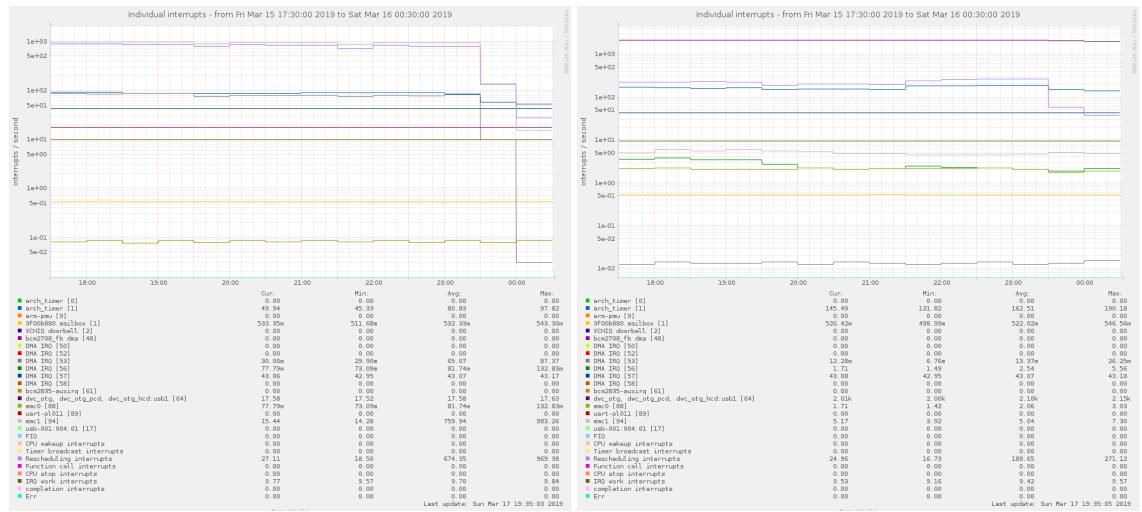


Figure 12.36: Mopidy Client and Server Device Individual Interrupts

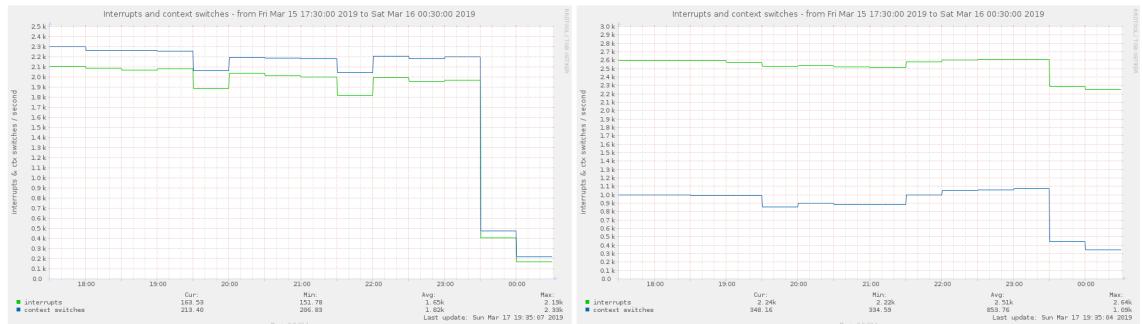


Figure 12.37: Mopidy Client and Server Device Interrupts and Context Switches

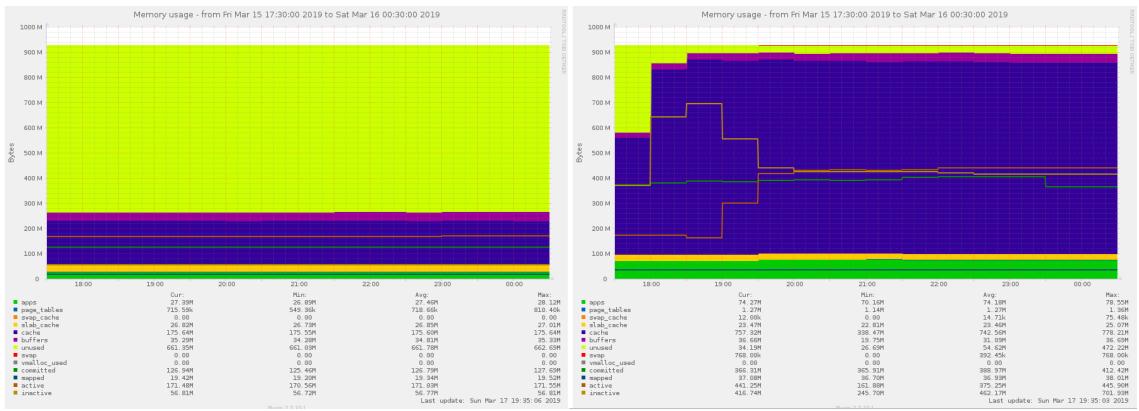


Figure 12.38: Mopidy Client and Server Device Memory Usage



Figure 12.39: Mopidy Client and Server Device Fork Rate

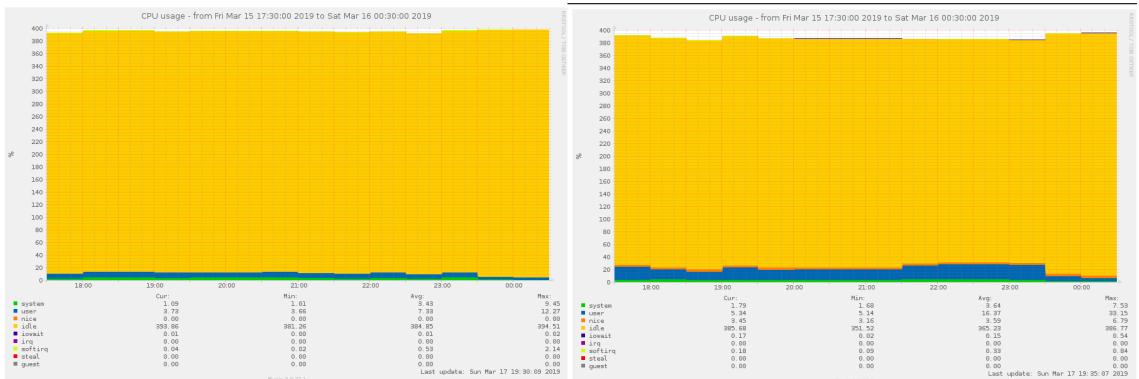


Figure 12.40: Mopidy Client and Server Device CPU Usage

## Sensors

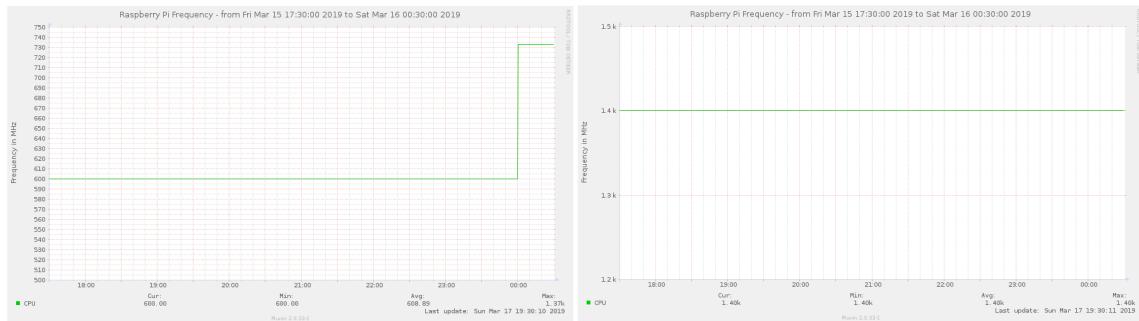


Figure 12.41: Mopidy Client and Server Device CPU Frequency



Figure 12.42: Mopidy Client and Server Device CPU Frequency Scaling



Figure 12.43: Mopidy Client and Server Device CPU Temperature

## Volumio

### Disk

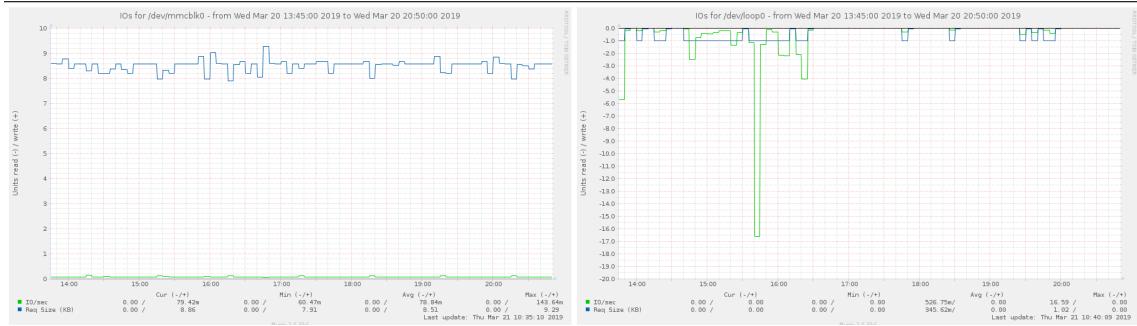


Figure 12.44: Volumio Disk I/O on Client and Server Device



Figure 12.45: Volumio Client and Server Device Disk Latency

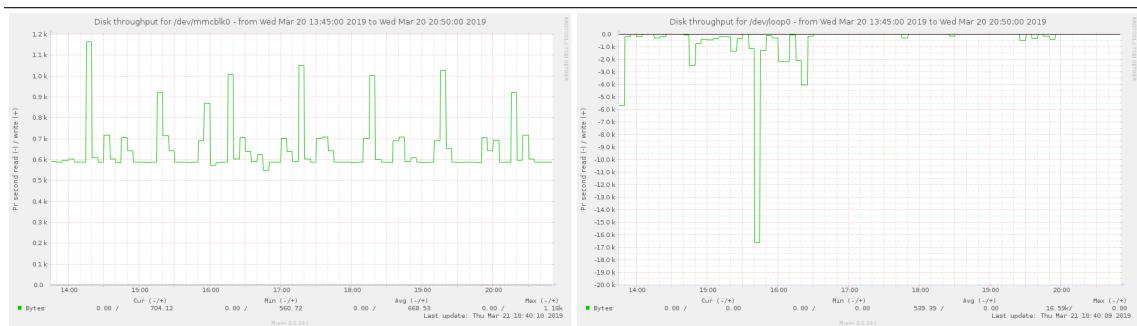


Figure 12.46: Volumio Client and Server Device Disk Throughput

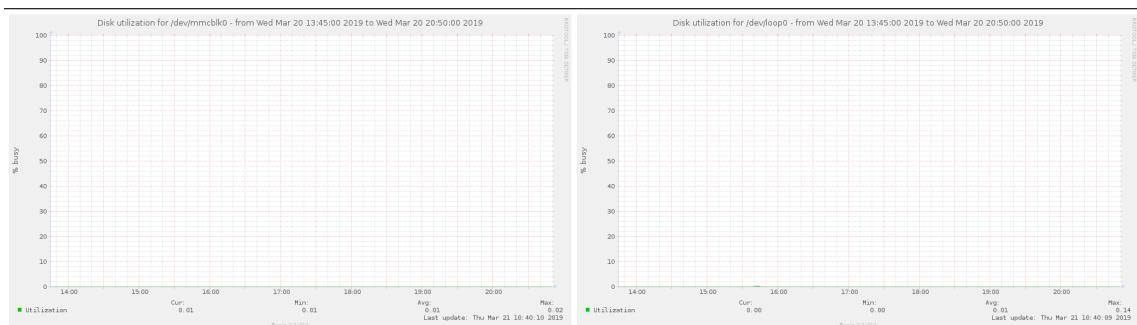


Figure 12.47: Volumio Client and Server Device Disk Utilization

## Network

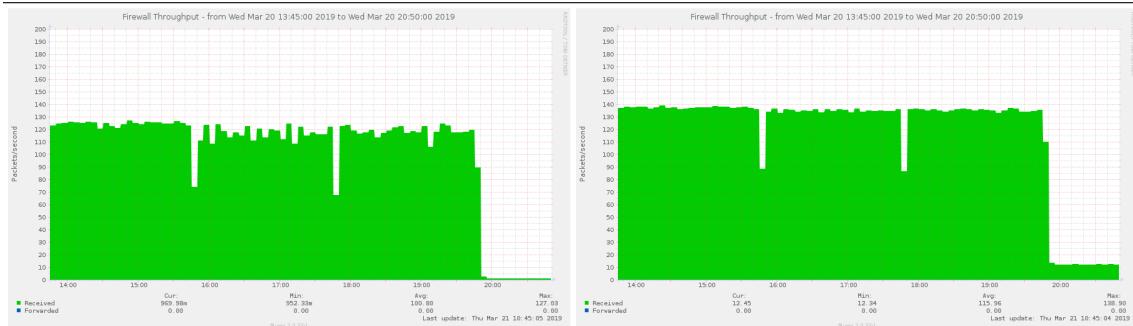


Figure 12.48: Volumio Client and Server Device Firewall Throughput

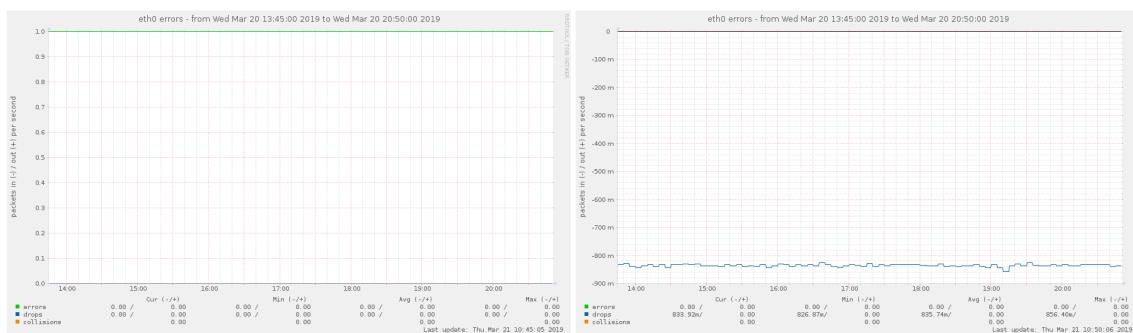


Figure 12.49: Volumio Client and Server Device Eth Errors

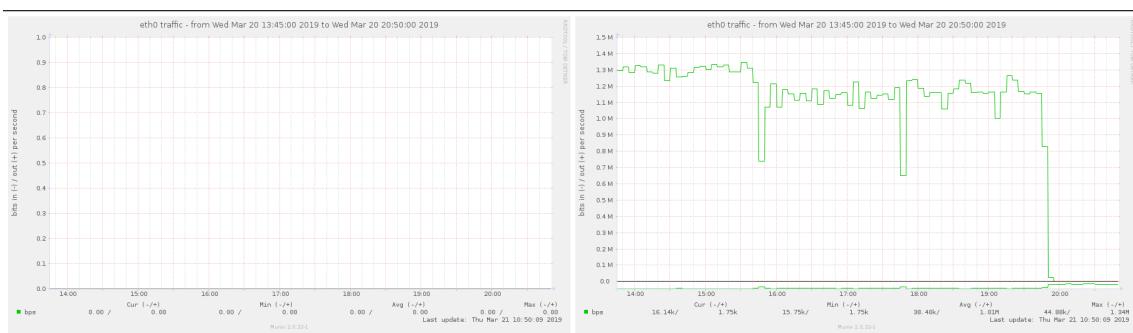


Figure 12.50: Volumio Client and Server Device Eth Traffic

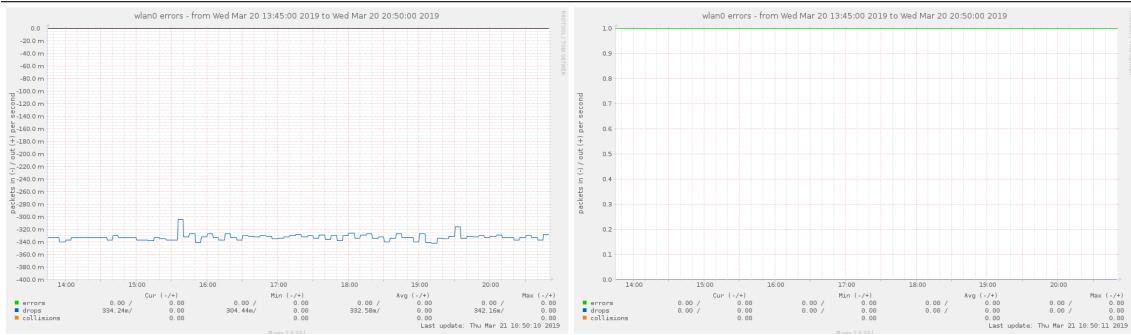


Figure 12.51: Volumio Client and Server Device Wlan Errors



Figure 12.52: Volumio Client and Server Device Wlan Traffic

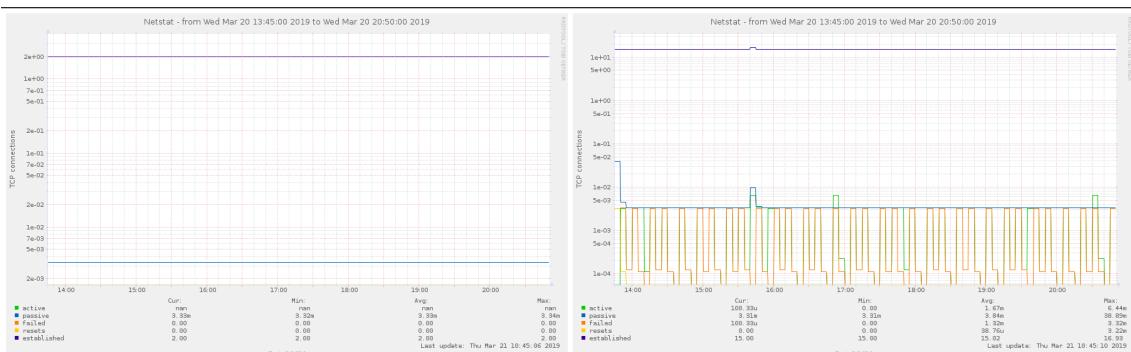


Figure 12.53: Volumio Client and Server Device Netstat

## Processes

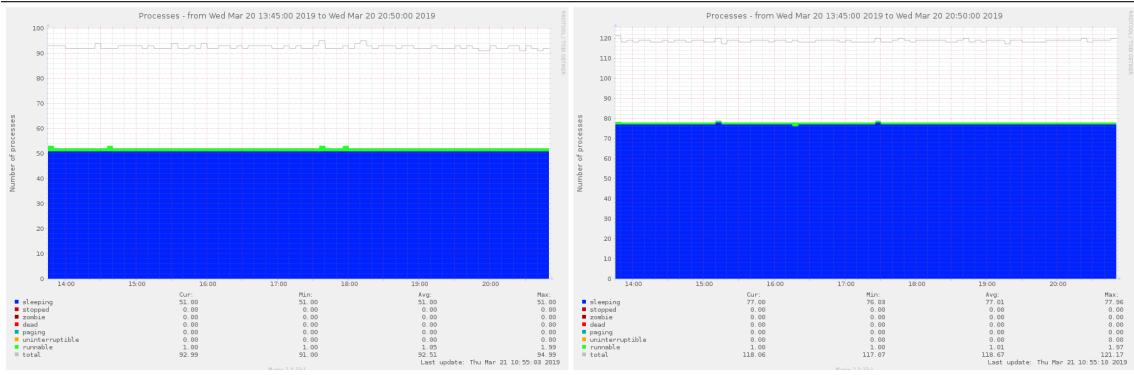


Figure 12.54: Volumio Client and Server Device Processes

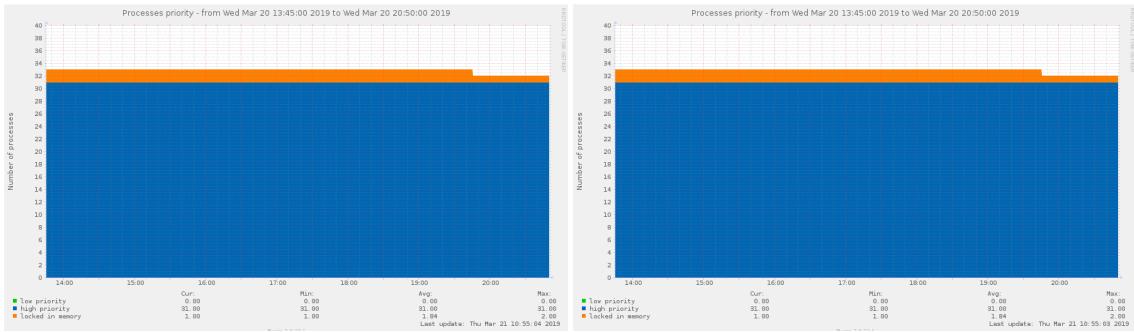


Figure 12.55: Volumio Client and Server Device Processes

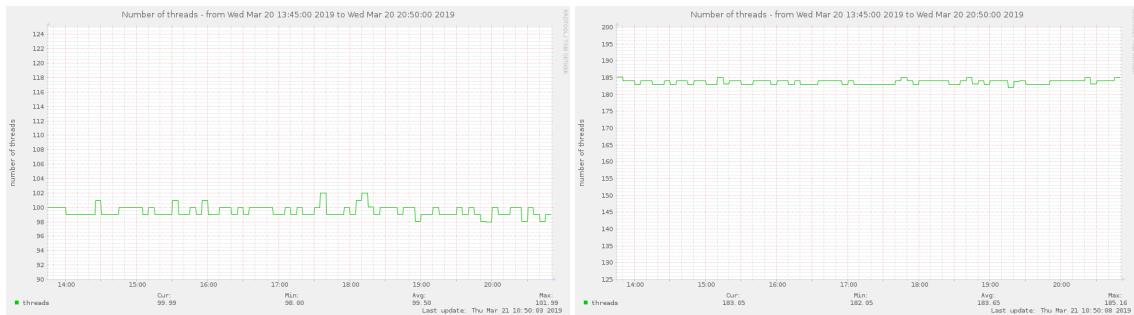


Figure 12.56: Volumio Client and Server Device Number of Threads

## System

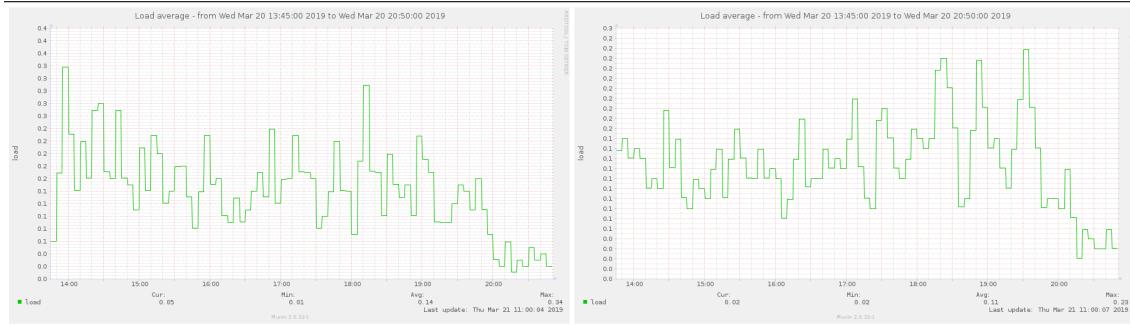


Figure 12.57: Volumio Client and Server Device Load Average



Figure 12.58: Volumio Client and Server Device Individual Interrupts

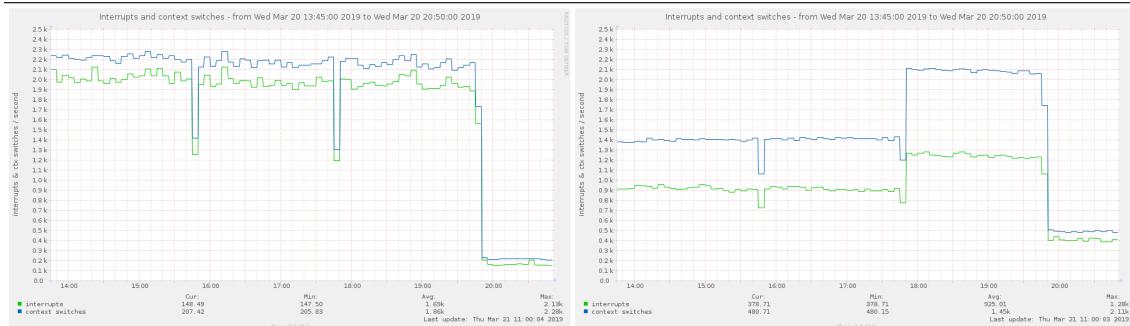


Figure 12.59: Volumio Client and Server Device Interrupts and Context Switches

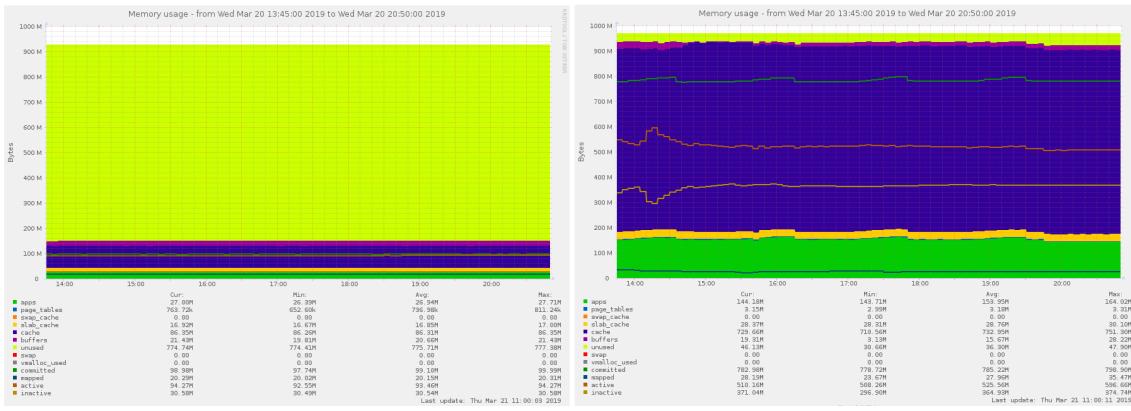


Figure 12.60: Volumio Client and Server Device Memory Usage

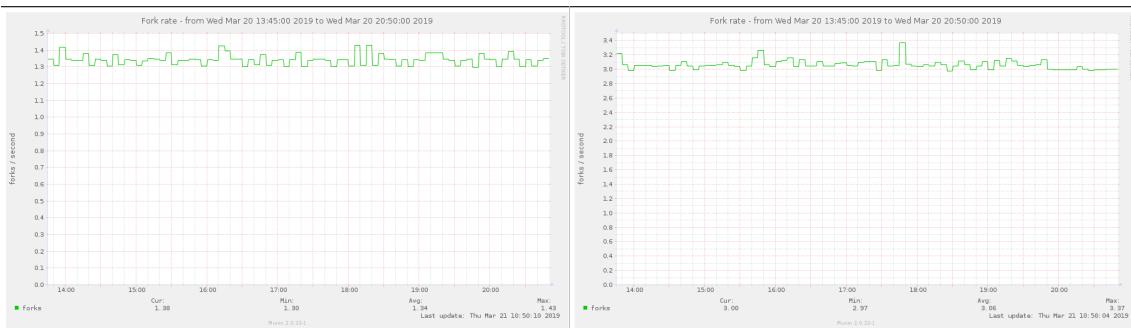


Figure 12.61: Volumio Client and Server Device Fork Rate



Figure 12.62: Volumio Client and Server Device CPU Usage

## Sensors

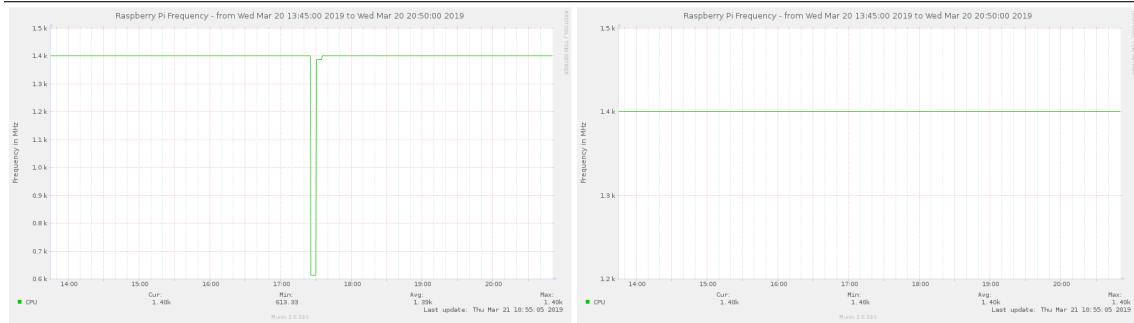


Figure 12.63: Volumio Client and Server Device CPU Frequency

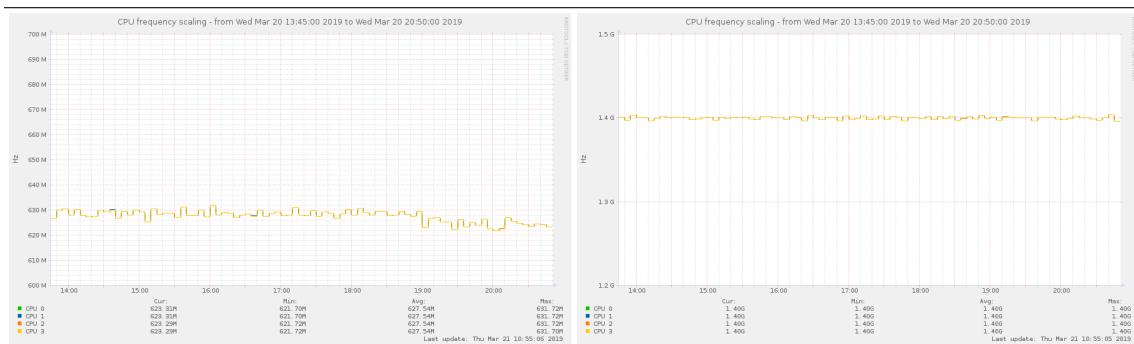


Figure 12.64: Volumio Client and Server Device CPU Frequency Scaling

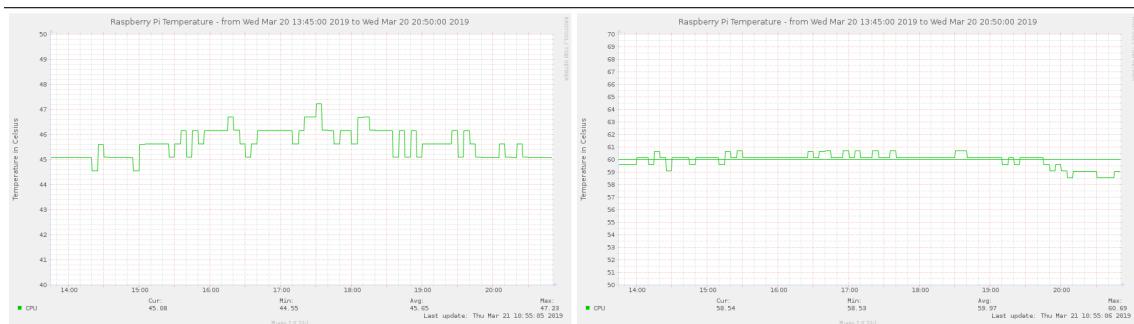


Figure 12.65: Volumio Client and Server Device CPU Temperature

## 12.2 Audio Server Software Munin Data Tables

### MPD

Disk (Client)						
Disk I/O						
	Min		Avg		Max	
	-	+	-	+	-	+
IO/sec	0.00	66.79m	0.00	82.31m	0.00	141.08m
Req Size (KB)	0.00	6.66	0.00	8.46	0.00	10.30
Disk Latency						
	Min		Avg		Max	
Device I/O Time	926.77u		1.60m		2.58m	
I/O Wait Time	4.20		7.32m		16.60m	
Read I/O Time	0.00m		0.00m		0.00m	
Write I/O Time	4.20m		7.32m		16.60m	
Disk Throughput						
	Min		Avg		Max	
	-	+	-	+	-	+
Bytes	0.00	453.23	0.00	697.68	0.00	1.23k
Disk Utilization						
	Min		Avg		Max	
Utilization (%Busy)	0.01		0.01		0.02	

Table 12.1: MPD SnapClient Device Disk Parameters

Disk (Server)						
Disk I/O						
	Min		Avg		Max	
	-	+	-	+	-	+
IO/sec	0.00	69.87m	252.42m	422.49m	1.03	536.13m
Req Size (KB)	0.00	6.40	113.98	6.98	296.23	8.55
Disk Latency						
	Min		Avg		Max	
Device I/O Time	397.44u		43.4m		10.33m	
I/O Wait Time	1.18m		6.21m		15.21m	
Read I/O Time	0.00m		7.65m		20.36m	
Write I/O Time	1.18m		3.00m		9.56m	
Disk Throughput						
	Min		Avg		Max	
	-	+	-	+	-	+
Bytes	0.00	572.00	59.27k	2.82k	185.35k	3.94k
Disk Utilization						
	Min		Avg		Max	
Utilization (%Busy)	0.00		0.39		1.17	

Table 12.2: MPD Server Device Disk Parameters

Network (Client)						
Firewall Throughput (Packets/sec)						
	Min		Avg		Max	
	-	+	-	+	-	+
Received	983.67m		99.33		126.69	
Forwarded	0.00		0.00		0.00	
Eth0 Errors						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	0.00	0.00	0.00	0.00	0.00	0.00
Collisions	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Traffic						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	0.00	0.00	0.00	0.00	0.00	0.00
Wlan0 Errors						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	270.53m	0.00	302.72m	0.00	343.80m	0.00
Collisions	0.00		0.00		0.00	
Wlan0 Traffic						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	669.92	1.58k	939.62k	31.80k	1.26M	39.03k
Netstat (TCP Connections)						
	Min		Avg		Max	
active	nan		nan		nan	
passive	3.31m		3.33m		3.35m	
failed	0.00		0.00		0.00	
resets	0.00		39.22u		3.26m	
established	2.00		2.26		3.00	

Table 12.3: MPD SnapClient Device Network Parameters

Network (Server)						
Firewall Throughput (Packets/sec)						
	Min		Avg		Max	
	-	+	-	+	-	+
Received	1.91		99.26		122.94	
Forwarded	0.00		0.00		0.00	
Eth0 Errors						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	830.03m	0.00	835.49m	0.00	853.19m	0.00
Collisions	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Traffic						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	1.25k	1.31k	23.66k	951.47k	29.07k	1.27M
Wlan0 Errors						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	327.00m	0.00	335.22m	0.00	349.93m	0.00
Collisions	0.00		0.00		0.00	
Wlan0 Traffic						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	186.42	17.12	321.71	22.45	741.32	39.21
Netstat (TCP Connections)						
	Min		Avg		Max	
active	nan		nan		nan	
passive	3.31m		3.33m		3.35m	
failed	0.00		0.00		0.00	
resets	0.00		39.22u		3.22m	
established	4.00		4.26		5.00	

Table 12.4: MPD Server Device Network Parameters

Processes (Client)						
Processes						
	Min		Avg		Max	
	-	+	-	+	-	+
Sleeping	50.00		52.23		56.00	
Uninterruptable	0.00		23.61m		973.33m	
Runnable	1.00		1.05		1.97	
Total	91.03		93.77		99.92	
Number of Threads						
	Min		Avg		Max	
Threads	98.03		100.80		106.97	

Table 12.5: MPD SnapClient Device Process Parameters

Processes (Server)						
Processes						
	Min		Avg		Max	
	-	+	-	+	-	+
Sleeping	52.01		54.27		58.00	
Runnable	1.00		1.04		1.99	
Total	94.01		96.30		100.99	
Number of Threads						
	Min		Avg		Max	
Threads	112.00		114.26		118.98	

Table 12.6: MPD Server Device Process Parameters

System (Client)			
Load Average			
	Min	Avg	Max
Load	0.02	0.13	0.46
Interrupts and Context Switches (/sec)			
	Min	Avg	Max
Interrupts	151.95	1.69k	2.10k
Active	208.25	1.87k	2.27k
Memory Usage (Bytes)			
	Min	Avg	Max
Active	164.04M	165.38M	167.67M
Inactive	51.14M	51.17M	51.21M
Unused	670.26M	673.18M	675.15M
Fork Rate (/sec)			
	Min	Avg	Max
Forks	1.30	1.34	1.50
CPU Usage (%)			
	Min	Avg	Max
System	1.05	3.35	9.27
Idle	381.73	384.41	394.69

Table 12.7: MPD SnapClient Device System Parameters

System (Server)			
Load Average			
	Min	Avg	Max
Load	0.03	0.41	1.03
Interrupts and Context Switches (/sec)			
	Min	Avg	Max
Interrupts	170.32	490.99	550.87
Active	250.84	742.53	898.79
Memory Usage (Bytes)			
	Min	Avg	Max
Active	270.40M	408.59M	437.63M
Inactive	424.17M	541.23M	589.36M
Unused	31.03M	35.88M	43.78M
Fork Rate (/sec)			
	Min	Avg	Max
Forks	1.30	1.39	1.70
CPU Usage (%)			
	Min	Avg	Max
System	1.21	5.89	15.08
Idle	363.71	369.60	394.16

Table 12.8: MPD Server Device System Parameters

Sensors (Client)			
CPU Frequency (MHz)			
	Min	Avg	Max
CPU	600.00	600.00	600.00
CPU Frequency Scaling (MHz)			
	Min	Avg	Max
CPU1	613.87	618.10	620.98
CPU2	613.92	618.10	620.97
CPU3	613.87	610.10	620.99
CPU4	613.92	610.10	620.98
CPU Temperature (°C)			
	Min	Avg	Max
CPU	41.86	42.66	44.00

Table 12.9: MPD SnapClient Device Sensor Parameters

Sensors (Server)			
CPU Frequency (MHz)			
	Min	Avg	Max
CPU	600.00	656.53	1.40k
CPU Frequency Scaling (MHz)			
	Min	Avg	Max
CPU1	624.32	691.30	842.15
CPU2	624.32	691.30	842.12
CPU3	624.30	691.30	842.14
CPU4	624.30	691.30	842.11
CPU Temperature (°C)			
	Min	Avg	Max
CPU	53.69	56.11	58.52

Table 12.10: MPD Server Device Sensor Parameters

## Mopidy

Disk (Client)					
Disk I/O					
	Min		Avg		Max
	-	+	-	+	-
IO/sec	0.00	57.86m	0.00	81.74m	0.00
Req Size (KB)	0.00	6.63	0.00	8.47	0.00
Disk Latency (sec)					
	Min		Avg		Max
Device I/O Time	891.70u		1.68m		3.20m
I/O Wait Time	4.00		7.65m		12.67m
Read I/O Time	0.00m		0.00m		0.00m
Write I/O Time	4.00m		7.65m		12.67m
Disk Throughput					
	Min		Avg		Max
	-	+	-	+	-
Bytes	0.00	422.65	0.00	695.06	0.00
Disk Utilization					
	Min		Avg		Max
Utilization (%Busy)	0.01		0.01		0.03

Table 12.11: Mopidy SnapClient Device Disk Parameters

Disk (Server)						
Disk I/O						
	Min		Avg		Max	
	-	+	-	+	-	+
IO/sec	0.00	1.01m	479.63m	2.05	2.39	3.64
Req Size (KB)	0.00	10.33	54.58	11.42	131.06	14.25
Disk Latency						
	Min		Avg		Max	
Device I/O Time	1.62m		3.24m		6.52m	
I/O Wait Time	23.95m		78.49m		105.33m	
Read I/O Time	0.00m		4.62m		10.31m	
Write I/O Time	30.35m		89.96m		185.33m	
Disk Throughput						
	Min		Avg		Max	
	-	+	-	+	-	+
Bytes	0.00	12.98k	54.91k	22.87k	176.23k	45.14k
Disk Utilization						
	Min		Avg		Max	
Utilization (%Busy)	0.24		0.88		2.05	

Table 12.12: Mopidy Server Device Disk Parameters

Network (Client)						
Firewall Throughput (Packets/sec)						
	Min		Avg		Max	
	-	+	-	+	-	+
Received	973.78m		96.31		126.42	
Forwarded	0.00		0.00		0.00	
Eth0 Errors						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	0.00	0.00	0.00	0.00	0.00	0.00
Collisions	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Traffic						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	0.00	0.00	0.00	0.00	0.00	0.00
Wlan0 Errors						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	313.56m	0.00	330.82m	0.00	344.32m	0.00
Collisions	0.00		0.00		0.00	
Wlan0 Traffic						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	181.87	17.17	280.87	22.18	756.88	31.00
Netstat (TCP Connections)						
	Min		Avg		Max	
active	nan		nan		nan	
passive	3.31m		3.33m		3.34m	
failed	0.00		0.00		0.00	
resets	0.00		0.00		0.00	
established	2.00		2.00		2.00	

Table 12.13: Mopidy SnapClient Device Network Parameters

Network (Server)						
Firewall Throughput (Packets/sec)						
	Min		Avg		Max	
	-	+	-	+	-	+
Received	3.11		100.40		132.30	
Forwarded	0.00		0.00		0.00	
Eth0 Errors						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	827.43m	0.00	835.03m	0.00	852.73m	0.00
Collisions	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Traffic						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	1.23k	1.34k	25.65k	961.24k	35.72k	1.34M
Wlan0 Errors						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	329.11m	0.00	334.61m	0.00	347.44m	0.00
Collisions	0.00		0.00		0.00	
Wlan0 Traffic						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	636.24	1.58k	950.23k	34.74k	1.33M	48.40k
Netstat (TCP Connections)						
	Min		Avg		Max	
	active	nan	nan	nan	nan	nan
passive	6.65m		7.26m		26.15m	
failed	0.00		0.00		0.00	
resets	0.00		0.00		0.00	
established	6.00		6.00		6.00	

Table 12.14: Mopidy Server Device Network Parameters

Processes (Client)						
Processes						
	Min		Avg		Max	
	-	+	-	+	-	+
Sleeping	50.03		50.96		51.00	
Uninterruptable	0.00		11.07m		970.00m	
Runnable	1.00		1.06		2.00	
Total	91.00		92.53		94.92	
Number of Threads						
	Min		Avg		Max	
Threads	98.00		99.50		101.90	

Table 12.15: Mopidy SnapClient Device Process Parameters

Processes (Server)					
Processes					
	Min	Avg	Max		
	-	+	-	+	-
Sleeping	57.03	58.88	60.97		
Uninterruptable	0.00	0.00	0.00		
Runnable	1.00	1.62	2.98		
Total	100.00	101.47	103.00		
Number of Threads					
	Min	Avg	Max		
Threads	126.00	133.41	137.97		

Table 12.16: Mopidy Server Device Process Parameters

System (Client)			
Load Average			
	Min	Avg	Max
Load	0.02	0.11	0.26
Interrupts and Context Switches (/sec)			
	Min	Avg	Max
Interrupts	151.78	1.65k	2.19k
Active	206.83	1.82k	2.33k
Memory Usage (Bytes)			
	Min	Avg	Max
Active	170.56M	171.03M	171.55M
Inactive	56.72M	56.77M	56.81M
Unused	661.03M	661.75M	662.69M
Fork Rate (/sec)			
	Min	Avg	Max
Forks	1.30	1.34	1.46
CPU Usage (%)			
	Min	Avg	Max
System	1.01	3.43	9.45
Idle	381.26	384.85	394.51

Table 12.17: Mopidy SnapClient Device System Parameters

System (Server)			
Load Average			
	Min	Avg	Max
Load	0.05	0.23	0.40
Interrupts and Context Switches (/sec)			
	Min	Avg	Max
Interrupts	2.22k	2.51k	2.64k
Active	334.59	853.76	1.09k
Memory Usage (Bytes)			
	Min	Avg	Max
Active	161.88M	375.25M	445.90M
Inactive	245.70M	462.17M	701.93M
Unused	26.69M	54.62M	472.22M
Fork Rate (/sec)			
	Min	Avg	Max
Forks	2.38	2.72	2.97
CPU Usage (%)			
	Min	Avg	Max
System	1.68	3.64	7.53
Idle	351.52	365.23	386.77

Table 12.18: Mopidy Server Device System Parameters

Sensors (Client)			
CPU Frequency (MHz)			
	Min	Avg	Max
CPU	600.00	608.89	1.37k
CPU Frequency Scaling (MHz)			
	Min	Avg	Max
CPU1	611.73	616.29	620.02
CPU2	611.73	616.29	620.02
CPU3	611.73	616.29	620.02
CPU4	611.73	616.29	620.02
CPU Temperature (°C)			
	Min	Avg	Max
CPU	43.48	44.63	46.14

Table 12.19: Mopidy SnapClient Device Sensor Parameters

Sensors (Server)			
CPU Frequency (MHz)			
	Min	Avg	Max
CPU	1.40k	1.40k	1.40k
CPU Frequency Scaling (MHz)			
	Min	Avg	Max
CPU1	638.58	646.91	674.50
CPU2	638.58	646.91	674.50
CPU3	638.58	646.91	674.50
CPU4	638.58	646.91	674.50
CPU Temperature (°C)			
	Min	Avg	Max
CPU	56.93	58.94	60.15

Table 12.20: Mopidy Server Device Sensor Parameters

## Volumio

Disk (Client)						
Disk I/O						
	Min		Avg		Max	
	-	+	-	+	-	+
IO/sec	0.00	60.47m	0.00	78.84m	0.00	143.64m
Req Size (KB)	0.00	7.91	0.00	8.51	0.00	9.29
Disk Latency						
	Min		Avg		Max	
Device I/O Time	856.84u		1.48m		3.28m	
I/O Wait Time	3.78m		6.39m		17.66m	
Read I/O Time	0.00m		0.00m		0.00m	
Write I/O Time	3.78m		6.39m		17.66m	
Disk Throughput						
	Min		Avg		Max	
	-	+	-	+	-	+
Bytes	0.00	560.72	0.00	668.53	0.00	1.16k
Disk Utilization						
	Min		Avg		Max	
Utilization (%Busy)	0.01		0.01		0.02	

Table 12.21: Volumio SnapClient Device Disk Parameters

Disk (Server)						
Disk I/O						
	Min		Avg		Max	
	-	+	-	+	-	+
IO/sec	0.00	0.00	526.775m	0.00	16.59	0.00
Req Size (KB)	0.00	0.00	345.62	0.00	1.02	0.00
Disk Latency						
	Min		Avg		Max	
	Device I/O Time	0.00		44.04u		449.24u
I/O Wait Time	0.00	1.22m		11.15m		
Read I/O Time	0.00m		1.22m		11.15m	
Write I/O Time	0.00		0.00		0.00	
Disk Throughput						
	Min		Avg		Max	
	-	+	-	+	-	+
Bytes	0.00	0.00	539.39	0.00	16.59k	0.00
Disk Utilization						
	Min		Avg		Max	
	Utilization (%Busy)	0.00		0.01		0.14

Table 12.22: Volumio Server Device Disk Parameters

Network (Client)						
Firewall Throughput (Packets/sec)						
	Min		Avg		Max	
	-	+	-	+	-	+
Received	952.33m		100.80		127.03	
Forwarded	0.00		0.00		0.00	
Eth0 Errors						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	0.00	0.00	0.00	0.00	0.00	0.00
Collisions	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Traffic						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	0.00	0.00	0.00	0.00	0.00	0.00
Wlan0 Errors						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	304.44m	0.00	332.58m	0.00	342.16m	0.00
Collisions	0.00		0.00		0.00	
Wlan0 Traffic						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	631.61	1.60k	993.84k	31.64k	1.32M	39.29k
Netstat (TCP Connections)						
	Min		Avg		Max	
active	nan		nan		nan	
passive	3.32m		3.33m		3.34m	
failed	0.00		0.00		0.00	
resets	0.00		39.22u		3.26m	
established	2.00		2.00		2.00	

Table 12.23: Volumio SnapClient Device Network Parameters

Network (Server)						
Firewall Throughput (Packets/sec)						
	Min		Avg		Max	
	-	+	-	+	-	+
Received	12.34		115.96		138.90	
Forwarded	0.00		0.00		0.00	
Eth0 Errors						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	826.87m	0.00	835.74m	0.00	856.40m	0.00
Collisions	0.00	0.00	0.00	0.00	0.00	0.00
Eth0 Traffic						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	15.75k	1.75k	38.40k	1.01M	44.88k	1.34M
Wlan0 Errors						
	Min		Avg		Max	
	-	+	-	+	-	+
Errors	0.00	0.00	0.00	0.00	0.00	0.00
Drops	0.00	0.00	0.00	0.00	0.00	0.00
Collisions	0.00		0.00		0.00	
Wlan0 Traffic						
	Min		Avg		Max	
	-	+	-	+	-	+
bps	0.00	0.00	2.30	3.69	13.02	20.92
Netstat (TCP Connections)						
	Min		Avg		Max	
active	0.00		1.67m		6.44m	
passive	3.31m		3.84m		38.89m	
failed	0.00		1.32m		3.32m	
resets	0.00		38.76u		3.22m	
established	15.00		15.02		16.93	

Table 12.24: Volumio Server Device Network Parameters

Processes (Client)						
Processes						
	Min		Avg		Max	
	-	+	-	+	-	+
Sleeping	51.00	51.00	51.00	51.00		
Uninterruptable	0.00	0.00	0.00	0.00		
Runnable	1.00	1.05	1.05	1.99		
Total	91.00	92.51	92.51	94.99		
Number of Threads						
	Min		Avg		Max	
Threads	98.00	99.50	99.50	101.99		

Table 12.25: Volumio SnapClient Device Process Parameters

Processes (Server)						
Processes						
	Min		Avg		Max	
	-	+	-	+	-	+
Sleeping	76.03		77.01		77.96	
Runnable	1.00		1.01		1.97	
Total	117.07		118.67		121.17	
Number of Threads						
	Min		Avg		Max	
Threads	182.05		183.65		185.16	

Table 12.26: Volumio Server Device Process Parameters

System (Client)			
Load Average			
	Min	Avg	Max
Load	0.01	0.14	0.34
Interrupts and Context Switches (/sec)			
	Min	Avg	Max
Interrupts	147.50	1.69k	2.13k
Active	208.83	1.86k	2.28k
Memory Usage (Bytes)			
	Min	Avg	Max
Active	92.55M	93.46M	94.27M
Inactive	30.49M	30.54M	30.58M
Unused	774.41M	775.71M	777.38M
Fork Rate (/sec)			
	Min	Avg	Max
Forks	1.30	1.34	1.43
CPU Usage (%)			
	Min	Avg	Max
System	1.14	4.07	10.54
Idle	381.29	384.25	394.36

Table 12.27: Volumio SnapClient Device System Parameters

System (Server)			
Load Average			
	Min	Avg	Max
Load	0.02	0.11	0.23
Interrupts and Context Switches (/sec)			
	Min	Avg	Max
Interrupts	378.71	925.01	1.28k
Active	480.15	1.45k	2.11k
Memory Usage (Bytes)			
	Min	Avg	Max
Active	508.26M	525.56M	596.66M
Inactive	296.90M	364.93M	374.74M
Unused	30.66M	36.30M	47.90M
Fork Rate (/sec)			
	Min	Avg	Max
Forks	2.97	3.06	3.37
CPU Usage (%)			
	Min	Avg	Max
System	1.50	2.61	3.06
Idle	378.43	382.80	395.45

Table 12.28: Volumio Server Device System Parameters

Sensors (Client)			
CPU Frequency (MHz)			
	Min	Avg	Max
CPU	613.33	1.39k	1.40k
CPU Frequency Scaling (MHz)			
	Min	Avg	Max
CPU1	621.70	627.54	631.72
CPU2	621.70	627.54	631.72
CPU3	621.72	627.54	631.72
CPU4	621.72	627.54	631.70
CPU Temperature (°C)			
	Min	Avg	Max
CPU	44.55	45.65	47.23

Table 12.29: Volumio SnapClient Device Sensor Parameters

Sensors (Server)			
CPU Frequency (MHz)			
	Min	Avg	Max
CPU	1.40k	1.40k	1.40k
CPU Frequency Scaling (MHz)			
	Min	Avg	Max
CPU1	1.40k	1.40k	1.40k
CPU2	1.40k	1.40k	1.40k
CPU3	1.40k	1.40k	1.40k
CPU4	1.40k	1.40k	1.40k
CPU Temperature (°C)			
	Min	Avg	Max
CPU	58.53	59.97	60.69

Table 12.30: Volumio Server Device Sensor Parameters

# Bibliography

- [1] BeagleBoard.org, “Beaglebone black,” 2018. [Online]. Available: <https://beagleboard.org/black>
- [2] Raspberry Pi Foundation, “Raspberry pi 3 model b+.” [Online]. Available: <https://www.raspberrypi.org/products/raspberry-pi-3-model-b-plus/>
- [3] Adafruit, “Overview | adafruit i2s audio bonnet for raspberry pi,” 2019. [Online]. Available: <https://learn.adafruit.com/adafruit-i2s-audio-bonnet-for-raspberry-pi/overview>
- [4] The Economist, “Having rescued recorded music, spotify may upend the industry again,” 2018. [Online]. Available: <https://www.economist.com/business/2018/01/11/having-rescued-recorded-music-spotify-may-upend-the-industry-again?frsc=dge>
- [5] ASUS, “Asus tinker board.” [Online]. Available: <https://www.asus.com/ie/Single-Board-Computer/Tinker-Board/>
- [6] HiFiBerry, “Hifiberry dac+ pro,” 2019. [Online]. Available: <https://www.hifiberry.com/shop/boards/hifiberry-dac-pro/>
- [7] PulseAudio, “Pulseaudio,” 2014. [Online]. Available: <https://www.freedesktop.org/wiki/Software/PulseAudio/About/>
- [8] T. M. P. D. Project”, “Music player daemon 0.21.4 documentation,” 2018. [Online]. Available: <https://www.musicpd.org/doc/>
- [9] Volumio, “Volumio documentation,” 2018. [Online]. Available: <https://volumio.github.io/docs/index.html>
- [10] J. Park, J. Kim, and S. Kang, “Ble-based accurate indoor location tracking for home and office,” Computer Science & Information Technology, 2015.
- [11] J. Gjengset, J. Xiong, G. McPhilips, and K. Jamieson, “Phaser: Enabling phased array signal processing on commodity wifi access points,” School of Information Systems at Institutional Knowledge at Singapore Management University, 2014.
- [12] K. T. Ye Heejung, “Beamforming transmission in ieee 802.1ac under time-varying channels,” The Scientific World Journal, 2014.
- [13] A. Uddin Afaz, R. Arablouei, F. de Hoog, B. Kusy, R. Jurdak, and N. Bergmann, “Estimating angle-of-arrival and time-of-flight for multipath components using wifi channel state information,” Sensors, 2018.
- [14] AltBeacon.org, “Altbeacon - the open proximity beacon,” 2019. [Online]. Available: <https://altbeacon.org/>
- [15] Google Developers, “Beacons | google developers,” 2019. [Online]. Available: <https://developers.google.com/beacons/>

- [16] Android Developers, “Wi-fi location: ranging with rtt | android developers,” 2019. [Online]. Available: <https://developer.android.com/guide/topics/connectivity/wifi-rtt>
- [17] Max, “Creating altbeacon with raspberry pi using bluez example code,” 2018. [Online]. Available: <https://scribbles.net/creating-altbeacon-using-bluez-example-code-on-raspberry-pi/>
- [18] Radius Networks, “Android beacon library,” 2018. [Online]. Available: <https://altbeacon.github.io/android-beacon-library/eddystone-how-to.html>
- [19] A. Reltz, C. Sexton, and F. Varol, “Altbeacon protocol specification v1.0,” 2015. [Online]. Available: <https://github.com/AltBeacon/spec>
- [20] J. Pohl, “Snapcast json rpc control api,” 2018. [Online]. Available: [https://github.com/badaix/snapcast/blob/master/doc/json\\_rpc\\_api/v2\\_0.md](https://github.com/badaix/snapcast/blob/master/doc/json_rpc_api/v2_0.md)
- [21] Loup, “Beacons | flutter beacons plugin for android and ios,” 2018. [Online]. Available: <https://github.com/loup-v/beacons>
- [22] Sky UK, “Sky q hub wireless broadband & broadband router,” 2019. [Online]. Available: <https://www.sky.com/shop/broadband-talk/sky-hub/>
- [23] J. Pohl, “Configuring zones,” 2016. [Online]. Available: <https://github.com/badaix/snapcast/issues/54>
- [24] N. Bridoux, “Beacon scanner,” 2018. [Online]. Available: [https://play.google.com/store/apps/details?id=com.bridou\\_n.beaconsscanner](https://play.google.com/store/apps/details?id=com.bridou_n.beaconsscanner)
- [25] SSH Communications Security Inc., “Ssh (secure shell) home page,” 2019. [Online]. Available: <https://www.ssh.com/ssh/>
- [26] Munin, “Munin wiki start,” 2019. [Online]. Available: <http://munin-monitoring.org/>
- [27] Admin’s Choice, “Crontab - quick reference.” [Online]. Available: <https://www.adminschoice.com/crontab-quick-reference>
- [28] Systutorials, “mpc (1) - linux man pages.” [Online]. Available: <https://www.systutorials.com/docs/linux/man/1-mpc/>
- [29] BlueZ Project, “Bluez official linux bluetooth protocol stack,” 2018. [Online]. Available: <http://www.bluez.org/>
- [30] E. Upton, “Introducing turbo mode: up to 50% more performance for free - raspberry pi.” [Online]. Available: <https://www.raspberrypi.org/blog/introducing-turbo-mode-up-to-50-more-performance-for-free/>
- [31] Statista, “Number of spotify premium subscribers worldwide from 1st quarter 2015 to 4th quarter 2018 (in millions),” 2019. [Online]. Available: <https://www.statista.com/statistics/244995/number-of-paying-spotify-subscribers/>
- [32] K. Sehgal, “Spotify and apple music should become record labels so musicians can make a fair living,” 2018. [Online]. Available: <https://www.cnbc.com/2018/01/26/how-spotify-apple-music-can-pay-musicians-more-commentary.html>
- [33] W. Page and D. Safir, “Money in, money out: Lessons from cmos in allocating and distributing licensing revenue,” Music & Copyright Newsletter, 2018. [Online].

Available: [http://serci.org/congress\\_documents/2018/money\\_in\\_money\\_out.pdf](http://serci.org/congress_documents/2018/money_in_money_out.pdf)

- [34] J. Muikku, "Pro rata and user centric distribution models: A comparative study," Digital Media Finland, 2017. [Online]. Available: [http://www.digitalmedia.fi/wp-content/uploads/2018/02/UC\\_report\\_final\\_171213.pdf](http://www.digitalmedia.fi/wp-content/uploads/2018/02/UC_report_final_171213.pdf)
- [35] J. Poort, J. Quintais, M. A. van der Ende, A. Yagafarova, and M. Hageraats, "Global online piracy study," SSRN Electronic Journal, 2018. [Online]. Available: <https://www.ivir.nl/publicaties/download/Global-Online-Piracy-Study.pdf>
- [36] MUSO, "2017 annual piracy reports," 2018. [Online]. Available: <https://www.muso.com/magazine/global-piracy-increases-throughout-2017-muso-reveals/>
- [37] Statista, "Global small business streaming without music licenses in 2018," 2019. [Online]. Available: <https://www.statista.com/statistics/939333/illegal-music-streaming-by-business-owners-worldwide/>
- [38] W. Ashford, "Researchers raise privacy concerns about bluetooth low energy devices," 2015. [Online]. Available: <https://www.computerweekly.com/news/4500246790/Researchers-raise-privacy-concerns-about-Bluetooth-Low-Energy-devices>
- [39] N. Dunne, "Proximity marketing: Often creepy, but it doesn't have to be," 2017. [Online]. Available: <https://www.digitaletics.org/essays/proximity-marketing-often-creepy-it-doesnt-have-be>